THE DARK SIDE OF ATTENTION:
INHIBITION OF DISTRACTOR INFORMATION FACILITATES ATTENTION

by

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Abstract

Our ability to look around our environment and to be able to "focus" on some specific information in the environment seems effortless. Underlying this illusion are many complex interactions that make up what we define as *attention*. The majority of work in the attention domain is focused on how we attend *to* information or how attention is shifted *to* other information. However, the goal of this body of work is to understand the other side of this coin, the *dark side of attention*. Specifically, the dark side of attention, defined here, encompasses all of the inhibitory processes that support selection. Across several experiments, I probe many of these processes and attempt to understand how they interact with one another. In Chapter 1, I reviewed some of the foundational research on attention and propose why understanding inhibitory processes is critical for understanding attention. In Chapter 2, I examined whether *learning* to ignore specific to-be-ignored information can help facilitate visual search. I demonstrate that learning to ignore information can result in a benefit that is modulated by participants' time spent learning about the to-be ignored feature. In Chapter 3, I investigated whether early feature-based attention can be facilitated by suppression of distractor feature information when multiple distractor features are present in a display. Additionally, I also investigated whether the consistency of this information (i.e., learning to ignore) is what

facilitates inhibition driving early feature-based information. In Chapter 4, I investigated how attention is shaped by experiences, both lived and biologically driven. Specifically, I investigate the interplay of these two types of experiences, using food stimuli as a key example, to understand how experience influences the control of visual attention. In Chapter 5, I investigated one of the electroencephalographic markers that is utilized in many attention experiments and demonstrate that it has been misrepresented. It seems that the N2pc cannot reflect just an initial shift of attention, but rather reflects post-selection processing well beyond the initial shift of attention. In Chapter 6 I considered all of these findings in a larger framework for understanding the cognitive underpinnings of inhibitory processes.

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In 1966, Dr. Howard Egeth closed his dissertation with the following statement:

"It seems clear that until more is known about the processing of irrelevant information it will be difficult, if not impossible, to achieve a good understanding of the processing of relevant information."

It is difficult to express what a privilege it has been to not only continue this line of research with my doctoral work, but to do so under the mentorship of Dr. Egeth. I have many big things to thank Dr. Egeth for, but I am most thankful for the little things: always having an open door, being available to meet when I was stressed about basically everything, sending me interesting articles whenever they would come up, always forcing me to ask why and how (rather than what and where), and showing me what good research questions look like. Most importantly, Dr. Egeth made this entire process fun. I can honestly say that these six years of research together have been some of the most curiosity-driven fun I have ever had. If I ever become a 1/10th of the researcher that Dr. Egeth is, it will be one of my greatest achievements.

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"We have to continually be jumping off cliffs and developing our wings on the way down." ~Kurt Vonnegut

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-Corbin

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Chapter 1: Attention

Attention is inherently limited. Contrary to the feeling that we have a total grasp on all the comings and goings of the world around us, we can quickly feel that confidence fade the moment we try to text and drive (please don't do this), or when we are watching a critical point in a movie and someone requires our attention across the room. Early research on these phenomena suggests that there is a limitation of attentional resources; mainly there is a limit to how much specific info we can select from the large swath of information in the present world (Cherry, 1953, Stewart, 1821; and for an updated review see Wood & Cowan, 1995). However, why is it the case that despite this limitation we feel like we have conscious access to all the present visual information in our environment? This is the central question cognitive scientists studying *attention* have considered over the latter half century. More specifically, cognitive scientists have queried: how do we select relevant information while we simultaneously filter out irrelevant information?

The goal of the current research is to examine the role that ignoring plays in filtering out irrelevant information in our visual world. Furthermore, I aim to demonstrate that inhibitory processes play a much larger role in the selection of

information than previously credited. In order to set the stage for this topic, I will briefly review the relevant literature on attention.

What is attention?

Identifying and understanding the cognitive processes underlying attention are difficult. For example, even initially defining "attention" does not come as an easy task. You can try for yourself now: try to come up with a definition for attention that doesn't rely on using the word "attention." You might find that you use stand-in words like "filter" or "select." More to the point, identifying what processes are involved in attention and whether there are several "types" of attentional processes are up for debate. The challenge here, as with all scientific inquiry, is to come up with a parsimonious theory defining the nature of attention, what influences the allocation of attentional resources, and what does it mean to "pay attention." Below is an abbreviated history of the progress psychologists have made in defining the cognitive process of "attention."

While the definitional challenge above may seem trivial, psychologists have struggled with such a scenario for more than a century. In the early work on attention (e.g., James, 1890/1950), psychologists argued that to understand attention we only need to look within our own experience (e.g., our mental life) to understand the very nature of it. Along these subjective lines of exploration,

others tried to examine how this "attention" influences the perception of a stimulus. In particular, in the early days of attention research one hot debate questioned whether the allocation of attention to a stimulus modulated the "intensity" of that stimulus (Titchener, 1908). For example, introspective "experiments" from psychologists at this time investigated whether attending to some sounds over others made them sound louder, or whether attending to a red piece of paper made it appear more vibrant, colorful, and/or bright. Obviously, due to the nature of these thought experiments it was difficult to identify whether attention plays this kind of role in perception. Pashler (1998) and others suggest that these founding writers in psychology set the stage for how we investigate the nature of attention.

Years later with significantly more insight and even more empirical evidence in hand, Pashler (1998) argues in his excellent book, *The Psychology of Attention*, that despite the feeling that we might have some innate understanding of the nature of attention, we in fact know nothing about it. This isn't to say that our understanding of mental life is tricking us or is incorrect, rather the study of mental life doesn't allow us an inside look into explanations into a number of phenomena. More specifically, the self-inquiry into the nature of attention doesn't help us understand the underlying mechanisms and processes involved

in attention, but leaves us to use the word as a stand-in for any number of cognitive processes.

One good example of an empirical inquiry into the nature of attention is the research dissociating attention from eye movements. Specifically, it would be a safe bet to argue that most early philosophers studying attention would refer to eye movements to an object and a shift of attention to that object as the same process. (Note: Helmholtz had provided some demonstrations that attention and eye movements could be separated in some circumstances (Von Helmholtz, 1896).) However, influential work by Posner (1980) argued for covert shifts of attention independent of where the eyes were fixating. To support these claims, Posner conducted several orienting studies (Posner, 1980). Typically, the studies involved several common elements, for example to ensure that observers didn't move their eyes, they monitored eye movements and only used trials that contained no movements. Observers were often presented with a cue prior the onset of a search display. The cue could either be a fixation cross, which told participants that the relevant stimulus (e.g., a black square) was equally likely to appear on either side of the screen (left or right), or it could be an arrow pointing to the left or right. The arrow cue had an 80% chance of indicating the correct side (i.e., valid cue) and a 20% chance of indicating the incorrect side

(i.e., invalid cue). After the cue was presented, the stimulus would appear on the screen and observers made a response. Depending on the particular task, sometimes observers were told to press a single button as quickly as possible when the stimulus appeared, no matter the location (i.e., a simple RT, which was used to eliminate overt response preparations), however typically they would make a two alternative forced choice response to indicate the location of the stimulus (i.e., left or right). Results from these studies revealed that when the arrow cue was presented, reaction times were drastically different for valid cues compared to invalid cues. Specifically, they found that when observers were presented an invalid cue they were much slower at responding to the stimulus compared to the valid cue, suggesting that attention was brought to the cued location independent of the location the eyes were fixating. As Posner (1980) argues, evidence such as this flies directly in the face of our notions that we have a total grasp on the visual comings and goings of the world around us. Specifically, even though Posner's task is quite simple, it presents findings suggesting that attention can only be in one location at a time. Furthermore, it also demonstrations how attention is limited in the other non-cued locations. This is very different from the feeling that we can consciously access any visual event that is in front of us. Rather, even within the information that is in our visual field there is only a small percentage that we can successful attend to.

Overall, by using empirical methodology, similar to what Posner did, we can probe the underlying processes involved in "attention" and, better yet, ask whether attention is made up of multiple cognitive functions, or is in itself a single cognitive process.

How do our goals and information in the world interact to influence attention?

Over the better part of a century, cognitive psychologists continued to take the approach laid out by researchers like Pashler (1998) and have operationalized cognitive phenomena that are related to the concept of attention. In the present stage of cognitive research on attention, most researchers would still argue for some form of what Pashler has laid out: probe cognitive processes through empirical exploration of various attention related phenomena and make connections between the phenomenological outcomes and some proposed unifying theory of attention. Specifically, many of the "unifying" theories describing the cognitive process of attention depend on a dichotomy of two attentional processes (see Figure 1.1 for visual example): bottom-up vs. top-down attention (Bacon & Egeth, 1994; Bundesen, 1990; Bundesen, Habekost, & Kyllingsbæk, 2005; Jonides & Yantis, 1988; Leber & Egeth, 2006; Theeuwes, 1994, 2010; Treisman & Gelade, 1980; Wolfe, 1994b; Wolfe, Cave, & Franzel, 1989; Wolfe & Gancarz, 1997; Wolfe & Horowitz, 2017; Wolfe, Reijnen, Van

Wert, & Kuzmova, 2009). How do various attentional phenomena map onto the theoretical dichotomy?

Bottom-up Attention

Bottom-up (or stimulus-driven) attention has previously been defined as: "involving the involuntary, unavoidable capture of attention by a salient perceptual stimulus" (Yantis, 2013). Therefore, bottom-up attention is the capture of attention, or the focusing of attention, on a particular stimulus that is solely driven by information from the environment. Moreover, *salient perceptual stimulus* refers to stimuli that have a differential signal compared to other perceptual stimuli that are available. For example, depending on your current task, a single red square among green squares will often grab your attention just as will a tilted line among straight lines. In the definition above, it seems that saliency is the most important factor for influencing stimulus driven attention. There are two critical examples that provide evidence for circumstances of stimulus driven attention: pop out search and abrupt onsets.

In the case of pop out search, experiments in this domain typically involve trials where a single target item differs from a homogenous set of non-target items. These salient target trials are compared to trials where the non-target items and

the target item are all heterogeneous (Note: not all pop out displays require homogenous non-target items, but many of them do involve homogenous non-targets, e.g., Triesman & Gelade, 1980). Results typically show that observers are faster at finding the target when it is more salient than the non-target items. In some cases, saliency has been defined using color as a feature. For example, Treisman and Gelade (1980) found that when the target item differed enough from the non-target items (e.g. a pink "O" among green O's), the search slopes were close to zero and independent of the display size. Thus, observers were able to quickly, and efficiently, find the target item. Researchers have defined instances when visual search for a target item is highly efficient as *parallel search* (Egeth, 1966; Treisman & Gelade, 1980). In the example above, efficient search occurs because pink O is salient in relation to the homogenous green Os. Rapid attentional selection due to a salient feature has also been shown using other features like orientation and shape (Treisman & Souther, 1985), luminance (Nothdurft, 1993), and texture information (Julesz, 1981). The take-home from the examples above is that bottom-up attention is rapidly drawn to certain stimuli that are salient, in the absence of any previous knowledge in the mind/brain of the searcher. In the referenced examples, the observers had no experience with any of the displays, yet when the display is shown, attention was

quickly oriented to the salient item in each display and thus attention was guided by the stimulus information.

Another example of when behavior is guided by bottom-up factors is the case of abrupt onsets. What is interesting about abrupt onsets is that despite the high similarity of non-target items and target items (e.g. black letters), by modulating the spatiotemporal qualities of a subset of the display items, we can influence where attention is allocated. Specifically, Jonides and Yantis (1988) found that when observers were instructed to find a specific letter (e.g. the letter S), reaction times were significantly faster if the target letter appeared abruptly at a location where no letter had been before, while the other non-target letters were slowly revealed behind masking placeholders. In contrast, this can work in the opposite direction where reaction times are often slower when a distractor is the item that abruptly onsets (Schreij, Owens, & Theeuwes, 2008), thus the abrupt onset guides attention to the distracting item. Therefore, it seems that although the objects in the paradigm mentioned above shared many features: shape (i.e. letters) and color, the spatial and temporal presentation of an item can influence where attention is guided.

Above I have described some cases where behavior can be influenced by information from the environment. These instances support the generalization that in most cases when items are salient compared to the background and other non-salient objects, typically attention is guided to these items quickly and efficiently. However, there have been alternative accounts suggesting that salient information does not always capture attention(Folk, Remington, & Johnston, 1992; Schreij et al., 2008). For example, work by Folk et al. (1992) suggests that this "bottom up" attentional capture only occurs when these salient items, even if they are distractors, are related and relevant to the attentional set the observer makes to find a target. For example, if a distractor is characterized by abrupt onsets, its presence only has a reaction time cost when the target is also characterized by abrupt onsets but not when the target is characterized by a different color.

Top-down Attention

Top-down (or goal-oriented) attention has previously been defined as: "deliberately paying attention to something in order to get information needed to achieve goals" (Yantis, 2013). However, there are circumstances where previous experience can influence attention and this might not be deemed as "deliberately paying attention". Therefore, I suggest that top-down attention

might be defined as any instance where attention is guided as a function of information stored in the central nervous system (independent of whether that is deliberate or not). To support the previous statement, we should consider an example of implicit memory guiding attention. In a study by Fischler (1977), observers were asked if two letter strings were both words (i.e., a lexical decision task). On some trials the two words were unrelated (Head-Tree) and on some trials the words were related (Cat-Dog). Results demonstrated that even though observers were not explicitly instructed to attend to the relationship between the two words, they were faster on trials where the words were associated compared to trials where there we not related. This suggests that even though observers received no instructions indicating that they attend to the relationship of the words nor did they deliberately attend to this relationship, the known semantic relationship that is stored in long-term memory implicitly guided attention (Note: this might be more of a response bias or priming issue, but in both of those cases it would still be an example of "top-down" guidance in that previously learned information influenced current behaviors). Therefore, it seems that information that resides in memory can influence behavior, independent of whether it was deliberate or not. However, how does guidance influence behavior when we actively try to attend to specific information?

An example of when behavior is deliberately guided by top-down attention is when observers try to attend to current goal information. This is a case that we are probably the most familiar with, for example when we search our house for our car keys; we usually have a representation of what our car keys look like that guides our attention. In the laboratory, a number of studies have been done looking at the effects of goal-oriented attention on visual search (for reviews see Egeth & Yantis, 1997; Theeuwes, 2010). Specifically, a study by Wolfe et al. (1989) demonstrated circumstances where attention is guided by a deliberate goal set. Observers were asked to search for specific "triple conjunction objects" among various distractors. These objects were conjunctions of three features, e.g. the target might be a big (size), white (color), vertical (orientation) line, and distractors shared two of the features with the target. As the authors demonstrate, parallel processes guide attention to each of the simple features and search slopes are more efficient compared to searches that only involved simple conjunctions (e.g. searching for a red O among green Os and red Xs). These results suggest that when observers have a specific top-down goal, they are able to orient attention to the desired target and, at least in this case, this results in more efficient search.

Above I described simple examples of when information already stored in the central nervous system can influence behavior. One generalization that we can draw from these studies is that attention can be guided by previously established semantic relationships. Additionally, we can claim that when

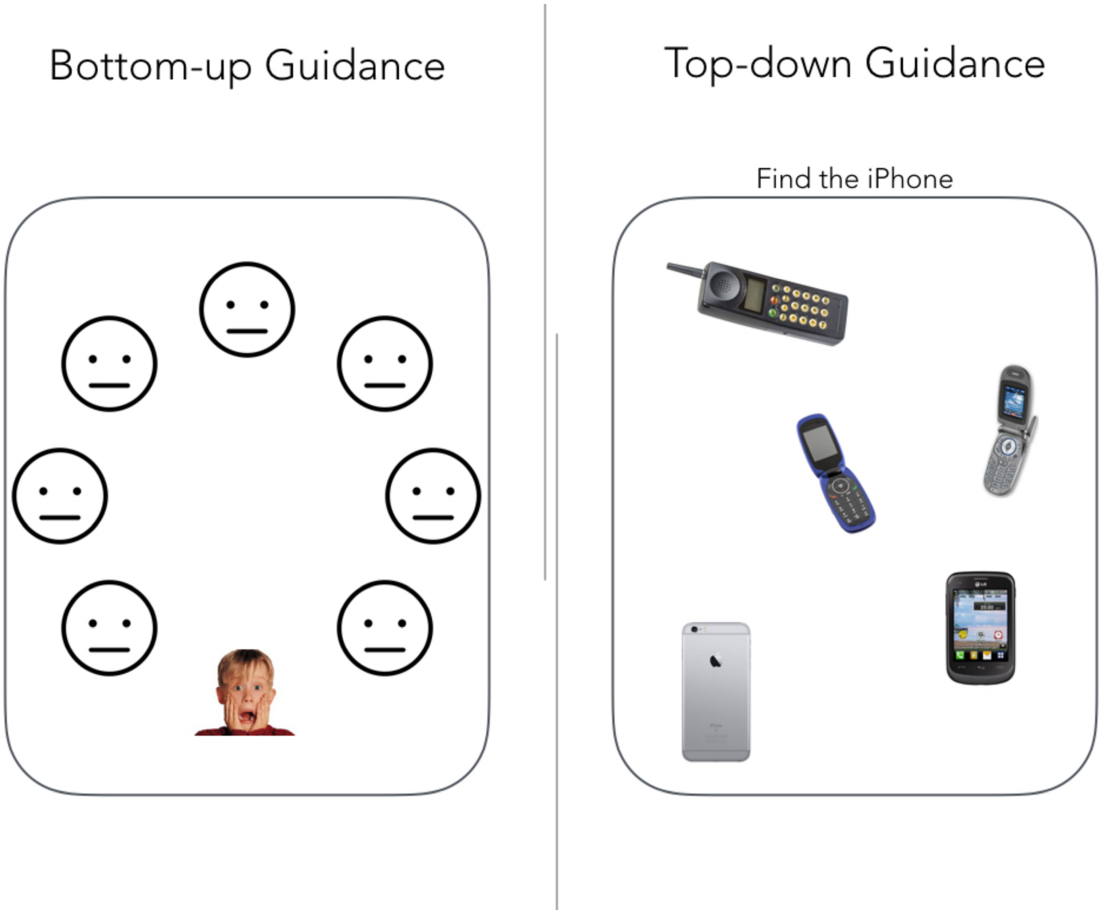

Figure 1.1 Examples of visual searches that use either Bottom-up or Top-down Guidance. On the left side, even without instructions it is very likely that your attention will be brought to the most salient item first (the surprised kid) rather than any of the other neutral faces, this attentional guidance is stimulus-driven. Alternatively, if you look at the search display on the right your attention to any of the items would be completely random, without the instructions at the top indicating that you should search for the iPhone; in this way attention is goal-driven.

observers want to deliberately find a specific item (e.g. our car keys), attention can be guided using feature information that is relevant to our target item.

However, it is not always the case that the generalizations made above hold in all circumstances.

But do we even need Bottom-up attention?

One very interesting idea put forth in recent work by Benoni (2018) suggests that while top-down and bottom-up attention is a parsimonious theory, evidence supporting Bottom-up attention, such as singleton capture experiments, could actually be explained by processes in top-down attention. Specifically, Benoni utilized a capture paradigm where 70% of the time observers could predict the location of a salient singleton distractor, and 30% of the time it was in an unexpected location. Results revealed a capture like effect on both the predicted and unpredicted trials. However, on the 30% of unpredicted trials observers were "captured" by the location of the expected singleton and not the actual singleton itself. Benoni (2018) argues that much of the work supporting cases of bottom-up driven attention (i.e., attentional capture by salient items) could actually by produced by top-down effects like these. Specifically, previous work in this domain has found support for bottom-up attention typically in tasks where there is a salient singleton, like the task above, that captures attention even though it is irrelevant to the observer's current

goals. However, Benoni suggests that the human visual system could actually be tuned to attend to irregular or salient events/items. It could be the case that the attentional system actually tags salient items as "relevant", even if they are different from current observer goals as a way to reduce information loss. Furthermore, Benoni presents a strong claim that we should "consider the possibility that all sources of attentional control by be represented by a continuous variable of top-down control" (Benoni, 2018).

Trichotomies are the new dichotomy

While the top-down vs. bottom-up dichotomy is still one of the most popular frameworks of attention, recent work has continued to test the boundaries of this theory and whether it holds up to the various attentional phenomena. For

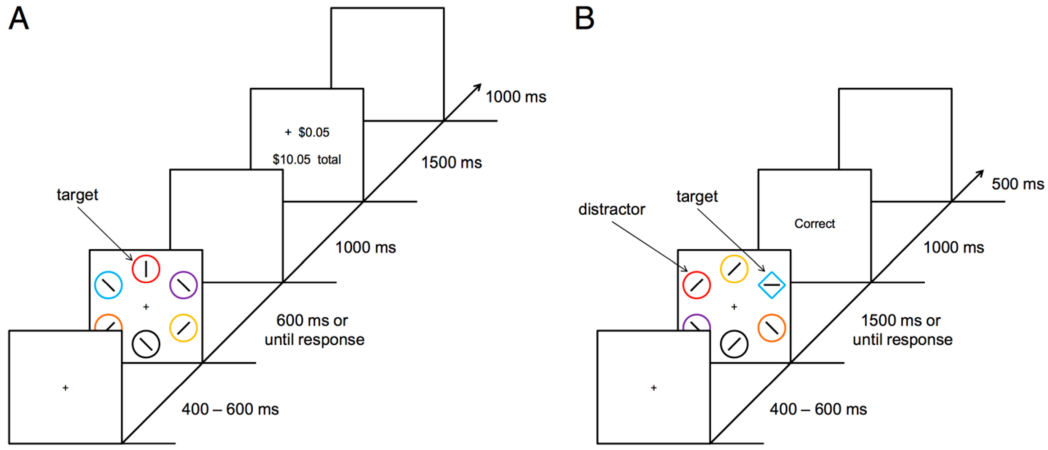

Figure 1.2 Example of a value-driven attentional capture study design. This layout was taken from Anderson, Laurent, and Yantis (2011).

example, recent work by Anderson, Laurent, and Yantis (2011) [also see: (Anderson, 2015, 2016a, 2016b; Anderson et al., 2016; Anderson, Laurent, & Yantis, 2013, 2014; Anderson & Yantis, 2012, 2013)] has argued that the bottom-up vs. top-down dichotomy is not enough. Specifically, they offer up a new *trichotomy* as a replacement with the following types of attentional guidance: stimulus-driven (i.e., bottom-up), goal-driven (i.e. top-down), and history-driven. Anderson et al. (2011) argue that their results could not be explained by the old dichotomy. Specifically, in their study they had two parts: a training phase and a test phase. In the training phase (see panel A in Figure 2) observers were told to search for targets that were either red or green, and to report the orientation of the line segment inside once they found one. A correct response for a red target would reward participants with, on average, a high-value reward ($0.05 80% of the time and $0.01 20% of the time), while finding a green target would reward participants with, on average, a low-value reward ($0.01 80% of the time and $0.05 20% of the time). Once participants completed 1,008 training trials, they started the test phase. In the test phase (see panel B in Figure 1.2), participants were informed that they would no longer be rewarded for any of their responses and color didn't matter for this task. Rather, the only goal the observers had was to look for an oddball shape (e.g., a single diamond among circles, or a single circle among diamonds). Once they located the singleton shape, they were

asked to report the orientation of the tilted line inside of that item. On a subset of trials in the test phase, one of the distractors was the color of the previous high-reward color (e.g., red) or the previous low-reward distractor (e.g., green). Results revealed that in the test phase, even when particpants were no longer rewarded, the reaction times were longer when a previously rewarded distractor was presented (either high or low) compared to when no previously rewarded distractor color was presented. Finally, while they found a monotonic trend as reward increased (distraction increased in this order: high-value distractor > low-value distractor > non-rewarded neutral distractor), there were no significant differences for the amount of distraction when a previously high or low reward distractor was presented.

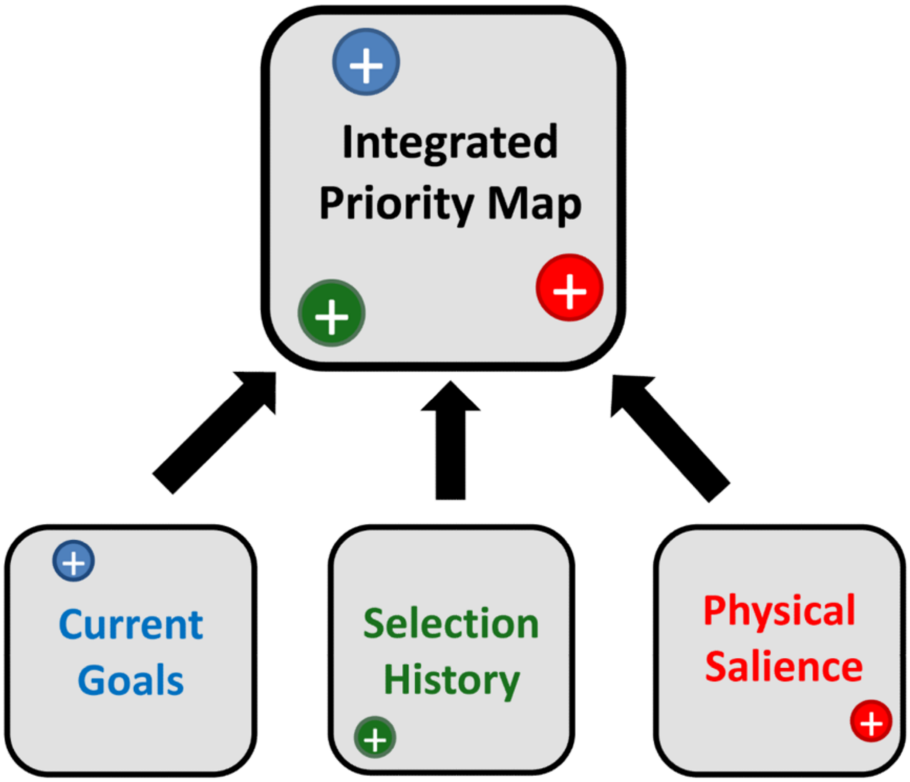

Figure 1.3 A schematic, proposed by Awh, Belopolsky, & Theeuwes (2012). This is illustrating input mechanisms that could influence attentional guidance.

Anderson et al. (2011) argue that because all items in the search displays in their test phase contained unique colors, their results couldn't be explained by *stimulus-driven* attention (i.e., the previously rewarded distractor didn't pop-out). Additionally, they argue that if observers had used *goal-driven attention*, then the partipants shouldn't have been captured at all by the distractors that were associated with a previous reward because the current goal for the participant was to search for an odd ball shape. Due to these conclusions, the

authors argue that the only alternative is that *value-driven attentional capture* is a third unqiue mechanism that guides search.

As more findings like the one detailed above have emerged, there has been a recent surge in the field of visual attenton to reform the old dichotomy of top-down and bottom up attention. One seminal paper on this topic put forth a formalized trichotomy that attempts to explain the interactions of value-driven attentional capture with the older dichotomy. Specifically, Awh, Belopolsky, and Theeuwes (2012), argue for three distinct mechanims in attentional guidance that feed into an "integrated priority map" (see Figure 1.3). They have a bottom-up/stimulus-driven mechanism that they call *Physical Salience.* They also include a mechanism called *Current Goals,* which emcompasses the typical top-down/goal-driven attentional guidance results. Finally, they have a new third mechanism called *Selection History*, which encompasses a variety of findings from value-driven attentional capture and other forms of past selection that influence attention. For example, while selection history does include the value effects described before, it also includes other forms of selction history like inter-trial priming (Maljkovic & Nakayama, 1994; Theeuwes & Van der Burg, 2007, 2011). Specifically, inter-trial priming describes a class of attentional effects where an item that was attended on a previous trial will influence attention on the current trial. For example, Maljkovic and Nakayama (1994) found that if

observers searched for the same feature two or more trials in a row (e.g., look for the red circle) then repeated search for the same feature would speed search on subsequent trials. Awh et al. (2012) argue that these effects can neither be described as bottom-up because they interact not only with the stimulus information but also with what the observer remembered/learned from the previuos trial. Additionally, the authors argue that they cannot be top-down because they are not the "current goal" of the observer. Due to this conundrum, Awh et al. (2012) argue the only plausible explaination is that there is a third mechanism guiding attention.

No-chotomies needed?

While it could easily appear that the solution to the old dichotomy explaining attentional guidance is to expand our definitions of distinct attentional mechanisms, other recent work has argued for the opposite. In the paper entitled "There is no such thing as attention" Anderson (2011) (not to be confused with Anderson mentioned above for the value driven attentional capture work) argued that psychologists' obsession with dichotomies have lead us down a road best not taken. Specifically, Anderson suggests that the current framework of attention is riddled with problems that have slowed the progress of attentional research, specifically suggesting that the insistence on

dichotomies create a framing problem. Due to this poor framing, psychologists attempt to "shoehorn" everything into "false dichotomies", resulting in a simplistic theory that does not apply to many generalized situations. While Anderson does argue against dichotomies such as preattentive vs. attentive processing or endogenous vs. exogenous cueing explicitly, he only hand-wavingly dismisses the top-down vs. bottom-up dichotomy. It is not surprising that Anderson didn't take on probably the biggest dichotomy in attention; this seems to be somewhat of a testament to how difficult it would be to argue that this dichotomy is definitively false. Although no one would argue that it has been *proven true,* some might argue that there is plenty of good evidence to buy into. Moreover, his "solution" to these psychological di/tri chotomies is to map biased competition theory (BCT) (Desimone & Duncan, 1995) onto Bayesian decision processes. However, the BCT that Desimone and Duncan (1995) put forth (which is detailed in the section on models below) is directly built on many assumptions about connections between top-down structures and bottom-up structures in the mind/brain. Specifically, top-down and bottom-up processes are inherently at odds with one another and drive the competition in many object interactions in the model. Furthermore, assuming that biased competition can be explained without top-down or bottom-up distinctions, we are still faced with an ever-growing model with degrees of freedom only bound

by researchers' creativity (i.e., what sources influence attention, which and how many are in direct competition with one another, do any of the sources interact, if so how?). The reason psychologists like Newell (1973) argue for dichotomies, or "binary oppositions", is not because it is the case that all aspects of the mind are broken up into this or that, rather it is because dichotomies provide an opportunity to compare psychological phenomenon, judge their similarity in process, implementation, or structure, and to draw *generalizable* conclusions about these attentional phenomenon. It is important to remember that we are in the business of predicting human behavior, so while dichotomies might not directly map onto the neuronal structure in the brain, they allow us an opportunity to plan a form of scholarly inquiry, e.g., is this phenomenon this or that? Overall, while Anderson (2011) provides a useful and critical review of psychology's dichotomy laden landscape, it does not seem particularly useful when considering what drives attention.

Why a dichotomy is enough

The goal of a theory is to create the most parsimonious explanation for a set of results. Up to this point I have provided some empirical evidence for the top-down vs. bottom-up distinction in visual attention. I described a recent review that, to say the least, was quite critical of that dichotomy (the paper is titled:

"Top-down versus bottom-up attentional control: A failed theoretical dichotomy"). Finally, I examined an outlier attempt to rid psychology of all dichotomies (Anderson, 2011). One might assume that at the very least this dichotomy should be put to rest, however I believe there is still a lot of utility left in the simple distinction of top-down vs. bottom-up attentional guidance. Moreover, I believe that none of the current tri-chotomies that have been recently presented provide any additional explanation beyond the top-down vs. bottom-up distinction.

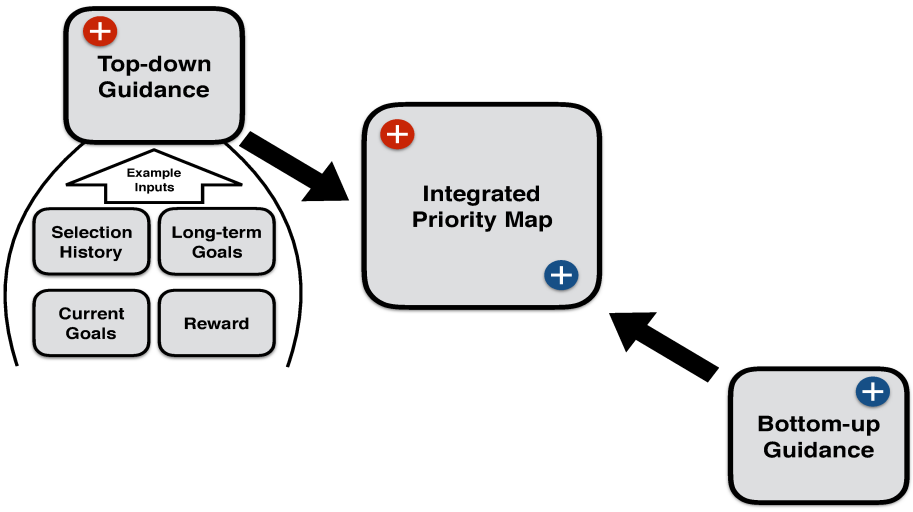

Figure 1.4 A schematic of a top-down & bottom-up driven attentional system.

This struggle to assess the utility of the old dichotomy vs. the new trichotomy has been subtly addressed in a recent review article by Wolfe and Horowitz

(2017). In their review, they provide a state of the field on what factors can guide attention. Their list includes five major factors: Bottom-up, Top-down, Scene-guidance, Reward-driven guidance, and Selection History. While the other forms of guidance have been discussed above, it is important to define scene-guidance. This form of guidance includes factors about a scene that can provide predictable information related to the location of certain items. For example, if you were looking for a bird you would generally look at the top of a scene (e.g., trees, sky, rooftops) rather than look to the ground (Biederman, Mezzanotte, & Rabinowitz, 1982). Wolfe and Horowitz (2017) do not attempt to provide a unifying theory to explain these results, rather they present the current evidence for these forms of guidance and suggest that: "modern theories of visual search need to incorporate all five factors and specify how these factors combine to shape search behavior." However, considering all the evidence put forth thus far, if we define top-down and bottom-up guidance in the following way, we are able to incorporate all five factors in the old dichotomy: *top-down attentional guidance* relies on any information learned prior to the current attentional event and *bottom-up attentional guidance* relies on information derived from the attentional event. In this way we can still rely on the integrated priority map theory suggested by Awh et al. (2012), however now we can consider the "maps" that each of these sources of guidance would use. In Figure 1.4 I've

displayed a quick schematic of how top-down and bottom-up attentional information could be integrated while accounting for the results of "other" forms of attentional guidance. In the same way that previous theories of visual attention have described how saliency maps drive bottom-up guidance (Bundesen, 1990; Bundesen et al., 2005; Wolfe, 1994a; Wolfe et al., 1989; Wolfe & Gancarz, 1997), we could also imagine a similar "saliency map" that would drive top-down guidance. For example, if we consider a typical value-driven attentional capture experiment, we have several top-down signals at play. Awh et al. (2012) would argue that we have selection history and current goals at play when trying to ignore a distractor that shares the same features as a previously rewarded item, while trying to find an unrelated unique target item. Furthermore, Sha and Jiang (2016) would argue that selection history in this case could include not only value information but also could include the act of simply selecting that item repeatedly in a previous task (i.e., inter-trial effects). However, it is not the case that these tasks exist in a vacuum. The participant who is sitting in the testing room also has other goals in mind: what they might do later that day, long-term survival based goals (e.g., how would their performance on a trial change if they smelled smoke at the moment of onset), and academic goals (e.g., if this student is doing this for credit, would a current goal not include to finishing this task as quickly as possible), etc. Should we not

create additional boxes in the Awh et al. (2012) model that would account for these inputs? Where would the number of boxes end? The idea here is to not be facetious, but to present how complicated the issue becomes when we start to think about how we might define a priority map and discretize the inputs in a similar way to Awh et al. (2012). Rather the schematic in Figure 1.4 presents an alternative account where all previously learned information (explicit or implicit) is in direct competition in the top-down map and this top-down map is then integrated into a priority map with the bottom-up map, similar to the activation map in guided search (Wolfe, 1994a). This simple theory still accounts for the results from selection history studies, as well as stimulus-driven and goal-driven results, without the need of total restructuring. In fact, there appears to be no evidence presented by Awh et al. (2012) that would require that the brain has to be implementing attentional guidance similar to the competition set up in their trichotomy. Therefore, the more parsimonious theory would be to still define attentional guidance into these two broad inputs as that which was previously learned (i.e., top-down) and that which was derived from the attentional event (i.e., bottom-up). It is important to note, that an even more parsimonious model for attention would be to only have one continuum, like what is argued by Benoni (2018). Specifically, Benoni's results can be explained by a single continuum of top-down attention and "bottom-up" like effects are actually

explained by the attentional system tagging salient items (due to a top-down set to attend to those items). While it is difficult to prove whether the classic dichotomy or a single continuum is the right answer, much of the work in attention (and the models below) rely on explanations supported by the classic bottom-up vs. top-down dichotomy.

Models of Attention: What and how do we select?

Identifying the possible signals that could be considered for selection is just one part of understanding the cognitive process of attention. However, another key factor to consider is how the attentional system actually selects information. Specifically, past attentional models have asked: what can the attentional system select (e.g., features, objects, etc), how is attention deployed to that information, and how does the selection occur? Below is a brief review of a few prominent models of visual attention.

When Selection Occurs

Early Selection – Broadbent

One of the earliest models of attentional processing was put forth by Broadbent (1958). In his model, he argued that when individuals are tasked with attending to a variety of information sources, that information is first put into a "buffer",

and then the information is selected or attended to. This model would later be categorized as an "early selection model", because information that is brought into the buffer isn't already fully processed rather it only becomes processed after selection. Support for his model was based on a variety of dichotic listening tasks (Broadbent, 1952; Cherry, 1953; Spieth, Curtis, & Webster, 1954). Typically, in these tasks the participant has two auditory sources of information, one in each ear. The participant is instructed to explicitly attend to one of the sources of information. For example, imagine that you hear a sequence of letters in your left ear simultaneous with a separate sequence of letters in your right ear. The participant is explicitly instructed to attend to the sequence in the right ear. Interestingly, when participants are asked to report the letters they heard, they will first report the attended sequence, *then* the unattended sequence. If they are forced to report them in the order they heard them (switching from left to right), then report performance severely drops due to having to switch between attention filters that are applied to the buffer. Broadbent took these results to suggest that all the items lived in the buffer, however the ability to accurately report the items depended on whether they were selected early.

Late Selection – Deutsch & Deutsch

In a theoretical review, Deutsch and Deutsch (1963) set forth to provide evidence against early selection models of attention, by arguing that all information is completely processed as it comes into the information processing system (which is counter to the early selection model which argues that information must first be placed in a buffer) . This theory was put forth in direct opposition to early selection. Some of the evidence for late selection includes findings from Peters (1954), which demonstrated that if you vary the similarity of the two streams of information in a dichotic listening task, the results show that higher similarity produces more interference. This would suggest that the content of both the unattended and attended streams are processed and then the cued information in one stream is selected. Additional evidence from Gray and Wedderburn (1960) found that when you present two different streams of information, one in each ear, that could be combined to create a meaningful sequence (e.g., Left Ear: “Is”, “this”, Right Ear: “Corbin's“, “Dissertation”, Combined: “Is this Corbin’s Dissertation”), even if participants are told to attend to one stream, they report the meaningful combination of the two. This also suggests that independent of where participants are cued, all of the information is processed for meaning. Deutsch and Deutsch (1963) argue that it cannot possibly be the case that there is early selection because if goal relevant information is to be selected, how does the system, in all cases, know which

incoming information is goal relevant without processing all information? It must be the case that on some level all possible information is processed and then that information which is most relevant to a current goal is subsequently selected.

What Do We Select

Feature Integration Theory – Treisman

While the work detailed above considers how information is selected after it is perceived, it is also important to consider when we "attend to" information in the world, what exactly are we selecting? Specifically, in the dichotic listening tasks detailed above, is the word in each of those tasks selected or just is the channel (ear) prioritized? Or is it some combination of the features, or the individual features that make up those words? Treisman and Gelade (1980) proposed the *Feature Integration Theory* which argued for a twofold process of selection. First, features (e.g., color, brightness, orientation) are processed rapidly and in parallel (to draw connections to the dichotic listening literature above, this could be features like pitch or loudness). Second, direct attention is required to identify objects that are described by multiple features. It is through attention that the assortment of features is recognized and combined into an "object". (Note: these findings bear resemblance to those of Egeth (1966), who

detailed the differences in Serial and Parallel processes.) Treisman and Gelade (1980) argue that in this case, attention is the "glue" that binds these seemingly unrelated features into an "object". The key argument in this theory is that without attention, an assortment of features remains just that, and will not obtain object-hood status. Evidence supporting this theory comes from a variety of cognitive tasks, including visual search and texture segmentation. For example, in their first experiment Treisman and Gelade (1980) investigated how search performance is impacted when observers search for an object defined by one dimension compared to search for an object defined by the conjunction of two dimensions. This was a replication of an earlier study by Treisman, Sykes, and Gelade (1977). Specifically, they had observers search for two features simultaneously: the color blue or the shape/letter "S". Critically, in the feature condition they could just search for either of the features alone to find the target, however in the conjunction condition they would need to search for the conjunction of two features (a green T). The authors found that even though observers were searching for an object in all cases, when they searched for an object defined by a single feature they performed the search in parallel and reaction times did not increase no matter how many other unrelated distractors were in the scene (even up to 30 items). In contrast, when observers had to search for an object defined by two features, search times were significantly

longer and increased as a function of the visual set size. Critically, it is important to note that in both cases they were always searching for two features, the only difference is that in the conjunction task they needed to be bound within the same item. The authors argue that because focal attention is required to "bind" the multiple features into a single object, this search can only be completed by a serial process of identifying whether both features are presented in the item that is being attended. However, when there is only a single defining feature, this search does not require binding and therefore can be completed using a parallel search process.

Parallel vs. Serial Search – Egeth, Virzi, Garbart

While the findings from Treisman and Gelade (1980) present a convincing argument for Feature Integration Theory (they have several other experiments in their paper identifying situations which suggest that conjunctions of multiple features require focal attention), there persists one problem in their designs. Specifically, Egeth, Virzi, and Garbart (1984) point out that in the displays constructed by Treisman and Gelade (1980) for their conjunction search conditions, the number of distractors that share a single feature with the conjunction target (e.g., Target = T_{green}, Distractors = S_{green} T_{pink}) increase directly as a function of the visual set size. This is because they had an equal number of

both kinds of distractors that each share a single feature with the conjunction target. Therefore, is it the case, as Treisman and Gelade argue, that conjunction search always *requires* a random serial search through the display or could it be that observers do perform a parallel search first through the scene, to reject a subset of irrelevant stimuli (here pink Ts), and then have to subsequently randomly serially search through the distractors and target that share 1 similar feature? If the latter were the case, we would still see similar search times as what was found by Treisman and Gelade since the number of rejected items in their displays increased with visual set size in a linear fashion. The latter argument seems much more parsimonious: all searches use the same type of search processes, a parallel sweep through the display, then a serial search through a subset of items that share a feature(s) if that is required to determine the target item. Therefore, to test this Egeth et al. (1984) fashioned displays where they varied the number of distractors in a conjunction search that share a feature with the conjunction target. Specifically, they presented observers with a search task where they had to find a red O. The distractors in these displays were black Os and red Ns. Critically, in some search conditions they presented observers with situations where a subset was held constant (e.g., always 3 red letters) and they varied the number of the "unrelated distractors" (e.g., in a target present search for 15 items: the red O is the target, there are 2 other red

Ns and 12 black Os; in the target present search for 22 items: the red O is the target, there are 2 other red Ns and 19 black Os). If we first search by using a parallel process and then a serial process, then holding the red subset constant should allow observers to produce flat search times (i.e., a parallel search) for the red O no matter how large the visual set size is, since there would always be a subset of 3 items. However, if it is the case that conjunction search requires a random serial search process, as suggested by Treisman and Gelade, then when observers search for the conjunction item even when the subset is held constant, then we should see search RTs increase as a function of visual set size. Surprisingly, Egeth et al. (1984) found that when observers were presented with search displays where one feature subset was held constant, they could easily perform a parallel search first through the subset and then identify their conjunction target within the subset (i.e., a subsequent non-random serial search). This resulted in flat search slopes as a function of visual set size (i.e., it didn't matter how large the visual set size was if the subset was held constant). Importantly, they found that when they kept the number of distractor items for each feature equal, search slopes were linearly increasing as a function of visual set size, similar to Treisman and Gelade (1980). These results suggest that search for a multidimensional item does not involve a subsequent random serial search after the massive parallel search.

Guided Search – Wolfe

Taking inspiration from previous work on search for objects defined by single and multiple dimensions (Egeth, 1966; Egeth et al., 1984; Hoffman, 1979; Treisman & Souther, 1985; Treisman et al., 1977; Treisman & Gelade, 1980) Wolfe and colleagues (Wolfe, 1994a; Wolfe et al., 1989; Wolfe & Gancarz, 1997) argue visual search requires several parallel searches (one for each feature of a multidimensional item) that then feed information forward into a subsequent serial search for the multidimensional item. For example, they would argue that search for triple conjunctions (e.g., a large, green, triangle) should be faster than search for conjunctions formed of two features because there is more information fed forward from the three parallel searches, compared to the two parallel searches required for a two-dimensional conjunction item. This would be counter-intuitive to the arguments made in Feature Integration Theory (Treisman & Gelade, 1980), which suggest that all conjunction searches would result in a serial search through the visual display until the target conjunction item is focally attended or the search is terminated. The key difference between Guided Search and Feature Integration theory is clearly the power given to the parallel search stage, which is where the "Guided" in Guided Search comes from. To support this theory, they directly tested visual search for a triple conjunction

items compared to an item defined by two features (Wolfe et al., 1989). Importantly they varied the similarity of the shared distractor features such that some triple conjunction searches involved distractors that shared one feature and some involved distractors that shared two features (see Figure 1.5 for an example of a triple conjunction). Overall, while increasing the distractor similarity (from one shared feature to two shared features) does bring search slopes closer to the typical search slopes of two feature conjunction items, in both cases search for a triple conjunction (e.g., a big, red, rectangle) item is significantly more efficient than search for a conjunction item with two features (e.g., a red rectangle).

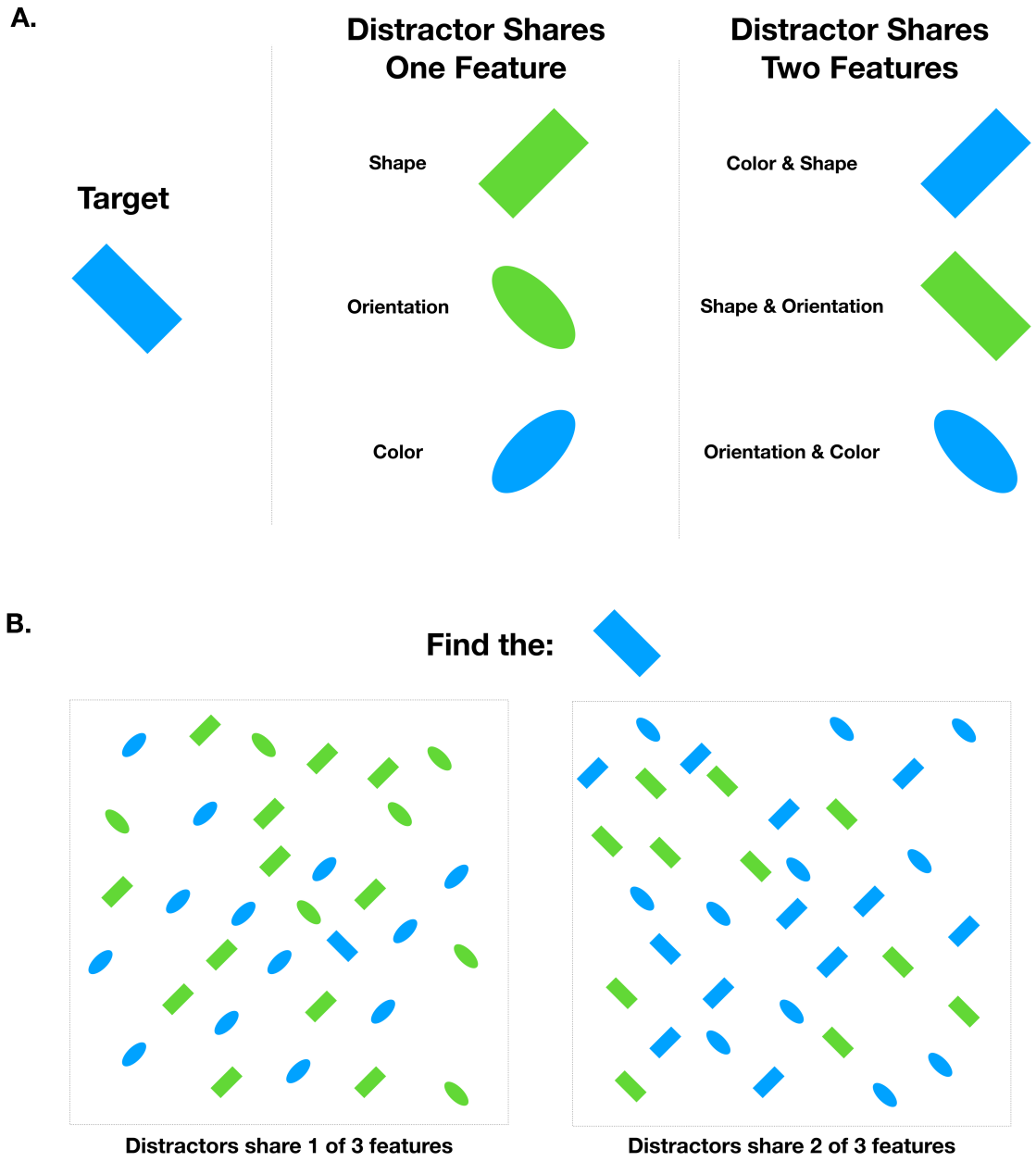

Figure 1.5 Example of a triple conjunction item and distractors that share either one or two similar features with the target. (A) The target has three possible features: orientation, color, and shape. In this case it is a blue, rectangle, tilted to the left. The distractor items either share one or two similar features with the target. (B) The low half of the figure shows two example search displays (the left is a double conjunction search and the right is a triple conjunction search) where you can try to find the target that is a blue rectangle, tilted to the left.

The guided search model has continued to be updated through the years (Wolfe, 1994a, 2001; Wolfe & Gancarz, 1997) to accommodate new findings in the visual attention literature. Critically, the newest version of Guided Search (4.0) includes a much more explicit framework including top-down commands for the activation of goal relevant features, which are then applied to a variety of weighted feature maps that are summed into a global activation map for the scene. In the activation map stage, attention is applied to items in decreasing amounts of activation (one could consider this a form a salience). Overall, this model has been updated to account for a variety of visual search phenomenon, with the main goal of the model focusing on understanding how humans search for a single target item.

Biased Competition – Desimone and Duncan

Desimone and Duncan (1995) Biased Competition theory argues that when we search for a target item, there is competition between all the objects in the scene. These items compete for attention (presumably after a massive parallel search across the scene), more specifically for representation and control. Competition in this theory is *biased* due to attentional processes related to both bottom-up and top-down guidance influencing the otherwise ambiguous competition. Specifically, information that is most physically salient will bias

attention, resulting in an increased amount of activity for that feature in the total competition of features . On the other hand, information that is currently goal-relevant, which would arguably be held in working memory, will bias competition for those features/items (e.g., searching for a T amongst Ls will bias competition for T-like features). For example, Desimone and Duncan (1995) argue that typical findings where conjunction search (e.g., find the red rectangle) is slow, compared to more bottom-up driven instances like pop-out search for a single feature (e.g., find the red item), arise from the lack of a single bottom-up feature to drive the competition. Thus, if the features across items are more similar, then the competition is more ambiguous and difficult to determine a "winner". However, in these situations competition for attention is still biased due to top-down control, more specifically through the use of "target templates" (Arita, Carlisle, & Woodman, 2012; Carlisle, Arita, Pardo, & Woodman, 2011; Duncan & Humphreys, 1989; Woodman, Vogel, & Luck, 2001). Similar to the framework set out in Guided Search (Wolfe et al., 1989), the top-down signals act upon the incoming bottom-up saliency map to bias competition for bottom-up information related to the goal-relevant content.

One of the critical differences between the Guided Search model of attention and Biased Competition, is that Biased Competition Theory was informed by

how neurons resolve competition. For example, it has been shown that neurons in visual areas respond considerably more when salient items land in their receptive fields (Allman, Miezin, & McGuinness, 1985) and that novel features (i.e., unfamiliar stimuli or stimuli not currently held in working memory) will result in higher neural responses compared to familiar features (Miller, Li, & Desimone, 1991). Additionally, prior work has shown that when monkeys were given specific top-down information about the location of a target item, neurons in V4 and IT both preferentially responded to the target item compared to a distractor item when they both landed in the receptive field (Moran & Desimone, 1985). Critically, no attentional modulations in the neural response were found when one of the two possible locations for the target item was placed outside of the receptive field. This suggests that when there was no longer competition between the distractor and target, the top-down information no longer needed to bias the competition.

Theory of Visual Attention – Bundesen

Bundesen's Theory of Visual Attention (TVA) and the neural implementation of this theory, the Neural Theory of Visual Attention (NTVA), present a mathematical framework for visual recognition of objects/features and how those items are selected (Bundesen, 1990, 1998; Bundesen et al., 2005;

Bundesen, Habekost, & Kyllingsbæk, 2011). Similar to the Biased Competition model, there is a competition, or in this case a "race", for visual information in a given scene to be encoded into visual working memory. This process is a considered a race due to the limited nature of visual working memory, such that these objects rapidly compete for space prior to VSTM "filling up" or reaching capacity. The vehicle for how these object race toward VSTM is built on perceptual categorization: does element *X* belong to category *y*. This perceptual categorization is formalized as a race model, which can determine the rate at which each item/object would make it into VSTM. Sensory information, attentional biases, and subject biases for categories, are all weighted when considering the likelihood that element X belongs to any given category. Once the weights are determined, all elements in a given scene are considered in the rate equation. The idea here is that if you can calculate the rate that each item would enter VSTM, you would know which items would be more or less likely to "grab attention" first. Obviously, while this model appears to have many similar elements to the precious models described above (mainly Guided Search and the Biased Competition models), the one key advantage is the formalized mathematical structure.

Models Summary

The frameworks put forth by the models above have primarily focused on when and how target/goal information is selected from the visual environment. Specifically, most of the architecture of these models are built to weigh dimensions to inform both serial and parallel searches for a *target item*. However, one interesting point to consider is how the *inhibitory* processes of attention interact with these target/goal processes. What is their role or contribution in these models? Can these models describe and predict the kinds of inhibitory attentional processes we've recently seen in the attention literature?

The Darkside of Attention: The Role of Inhibition in Visual Search

The majority of attention research to date has focused on how target and/or goal information is enhanced and, thus, selected. However, the act of enhancing target information also results in the system ignoring, or suppressing, other irrelevant information. What role does ignoring *irrelevant information* play in target selection? Does actively ignoring distracting information (e.g., a person loudly talking on the phone while you are working in an office) work? Specifically, does actively trying to suppress or ignore certain information end up making it harder because we are attending to it? Finally, do similar attentional mechanisms that support target selection also support inhibiting

non-target information? Below is a brief review of attentional research that focuses on inhibitory attentional mechanisms.

When Inhibiting Distractors "helps"

The ability to successfully suppress non-target information is critical in the ability to identify and locate target information in a timely manner. For example, when searching for a mug in the kitchen one might assume that if we are serially searching through a cabinet, we use information about the target to either accept or to reject items. However, what is obvious in this example is that there are several ways we could accomplish this search. One is to create an attentional template that matches our knowledge about the mug, wherein we compare each serially searched item to that template. However, it also could be the case that we hold some *template for rejection* in mind where we know some features that the mug will not have (e.g., it won't be totally flat like a plate). Do the attentional mechanisms in human vision support such a structure or do we only hold templates that match our goal information?

<u>When inhibiting distractors helps: Objects</u>

There is evidence in the literature that *visual marking* can allow for the efficient inhibition of distractors. Watson and Humphreys (1997) was one of the first

studies to demonstrate this effect. Specifically, they presented participants with a distractor preview phase prior to the presentation of the whole visual search trial. In the preview phase, they showed participants a subset of the distractors that would appear in the upcoming visual search trial. The authors found that when subjects were presented with this preview, they demonstrated search times to the entire display that reflected search times as if those previewed items were not in the display at all. The authors argued that participants were able to effectively "ignore" those previewed items and only had to search through the newly presented items.

Additional work by Donk and Theeuwes (2001) argued that the search benefit shown in visual marking was due to the abrupt onset of the other items (which contained the target) which captured participants attention, rather than the inhibition of the old previewed items. Thus, the search benefit was not due to any interesting form of inhibition, rather attention was merely more strongly guided to the information that abruptly onset at a later time. However, evidence from a dot probe study by Watson and Humphreys (2000) demonstrated that when previewed distractors were probed, response times were significantly longer compared to when non-previewed items were probed, suggesting that participants were actively inhibiting those previewed items. Moreover, this only

occurred when suppressing the item was advantageous; although their manipulation to reduce advantaged did change the task demands from involving visual search to only responding to probe trials. Thus, when considering these findings compared to the work of Donk and Theeuwes (2001), it seems that it could still be the case that the abrupt onset is might be driving the benefits shown in visual marking.

While much of the work on visual marking suggests that participants are inhibiting the location of the previewed items, recent work has also demonstrated that the features of those previewed items can be actively inhibited. For example, a number of studies by Braithwaite and Humphreys (Braithwaite & Humphreys, 2003; Braithwaite & Humphreys, 2007a; Braithwaite & Humphreys, 2007b; Braithwaite, Humphreys, & Hodsoll, 2003, 2004; Braithwaite, Humphreys, & Hulleman, 2005) have demonstrated that if the previewed items share a similar feature (e.g., all previewed distractors are red), that feature will be actively suppressed when the participant searches the full visual search display.

Taken together, the visual marking literature suggests that prior knowledge about to-be-ignored distractors can lead to more efficient search. However, is

the benefit from visual marking derived from a combination of location and feature information, or can there be a search benefit from knowing just the distractor location or the distractor feature information? Understanding the specificity of the required prior knowledge about distractor information would further elucidate the mechanisms that permit to-be-ignored information to aid in visual search.

When inhibiting distractors helps: Locations

There is evidence that when observers are provided information about where the location of a distractor will be, this can make subsequent search for a target more efficient. One clear example of this is a recent study by Ruff and Driver (2006). In their study, they had observers perform a speeded discrimination task. Specifically, on all trials they presented a cue, prior to the search display, in the form of a centralized arrow that pointed to the left or right which indicated the location where the target item would appear (it was 100% valid). There were two trial types: (1) target alone or (2) target with a distractor presented on the opposite side. Both trial conditions were presented randomly intermixed. Interestingly, they had two block types made up of these trial conditions: (1) an informative cue block and (2) a uninformative block. In the informative cue block, the color of the arrow (either red or green) would let subjects know

whether a distractor would be presented. In the uninformative block, the arrow didn't have a color cue and thus, was not predictive of whether a distractor would appear. While participants were overall slower when responding to the target in the presence of a distraction, the type of block they were in drastically changed their performance. Specifically, because the researchers had used the same trial types in both block conditions, they could look at the performance change as a function of predictive cue information. The authors found that in distractor present trials, participants were much faster when they were provided cue information from the arrow that a distractor would be present compared to trials where they weren't provided such information. Interestingly, when they compared responses on distractor absent trials in both the informative and uninformative blocks, they found no reaction time differences. The authors concluded that providing participants information about the location of a distractor allowed participants to avoid distraction by that item by inhibiting the location prior to the presentation of the visual search array.

While it is interesting that knowledge about the location of an upcoming distractor can facilitate search times for a target, one critical question is how does that knowledge actually speed search times? A study by Van der Stigchel and Theeuwes (2006) examined just that by investigating how previous

knowledge about a distractor position would influence eye movements to a target. In their study, they first presented participants with a central fixation. After 600 msecs, they replaced the fixation with two line segments that indicated where the target (e.g., a black circle) would be located and where the distractor (e.g., a diamond outline) could be. After a variable time period, the target would appear and participants were instructed to make an eye movement to the target as soon as it onset. Critically, on 80% of trials a distractor would appear adjacent to the target. Results revealed that when participants were informed of the distractor location and they were cued to it, they demonstrated a strong curvature in their eye movement trajectory to the target that was curved *away* from where the distractor was located. Furthermore, even on trials where a physical distractor was not presented (i.e., 20% of trials), because the participants were cued to where the distractor could be they still found significant curvature away from the cued location when participants made a saccade to the target. However, the curvature was diminished compared to when a distractor was actually shown. These results suggest that even possibility of a potential distractor being presented can influence eye-movements to avoid crossing over the distractor location and thus reduce the probability of being distracted by that item.

Both examples above of the ability to inhibit the location of a distractor rely on knowledge of not only the distractor but also where the target will be. One interesting question to consider is: does only providing information about a to-be-ignored distractor enable participants to search for an unpredictable target more efficiently? Munneke, Van der Stigchel, and Theeuwes (2008) were interested in identifying whether providing participants with an explicit to-be-ignored location cue would be enough to facilitate search performance for an uncued target. In their study, they had participants search for a capital letter "B" or "F" in one of four locations (0°, 90°, 180°, 270°). Prior to the search display, a precue was presented. On half of the trials, they cued participants to ignore a certain location because a distractor would be presented there. On the other half of trials, they provided no informative cue. These cues were 100% valid. In addition to having the target present in the search display, two of the other three locations contained random uppercase or lowercase letters "K" or "X". Critically, to look at congruency effects (similar to a flanker task, see Eriksen & Eriksen, 1974) they presented either a congruent or incongruent lowercase "b" or "f" in the fourth location. For example, if the target on a given trial was a capital "B", they could present either a congruent lowercase "b" or an incongruent lowercase "f". On the trials where the to-be-ignored location was cued, the distractor that was cued was always this congruent or incongruent

item. The results revealed that participants were generally faster on trials where a to-be-ignored item was cued compared to the trials where no cue information was provided. Importantly, because the authors included the compatibility manipulation they could examine whether the faster search times found in the to-be-ignored cued trials comes from processing that cued item and rapidly suppressing it or whether it comes from participants completely inhibiting the item at that location without processing the distractor. If it was the case that observers were processing and rejecting the to-be-ignored item, then they should be slower on incompatible trials compared to compatible trials in the cued condition. This is exactly what they found. Moreover, they also discovered that the compatibility effect was much larger in the cue condition compared to the uncued condition, which is probably due to the fact that in the cued condition participants are always initially attending to the to-be-ignored cued distractor. However, in the uncued condition since subjects would have to serially search through the 4 items until they land on the capital "B" or "F" it could very well be the case that many of the trials they were able to land on the target before they landed on the related distractor. Overall, these results suggest that to be able to use an explicit to-be-ignored location cue, the to-be-ignored distractor needs to be selected and then rejected.

The results from Munneke et al. (2008) suggest that when provided with a to-be-ignored location cue, observers need to actively select and reject the to-be-ignored distractor at that location. However, it could be the case that observers are not actively inhibiting that location, rather they are increasing the activation to the other 3 possible target locations. To investigate this, Chao (2010) queried whether providing three cues to the other possible target locations provided the same benefit as instructing participants to ignore one distractor location. Using a similar paradigm to Munneke et al. (2008), Chao (2010) found that providing location cues for the other three locations that might contain the target provided no additional benefit compared to control trials where no valid cue was provided. These results suggest that the benefit that arises from providing a to-be-ignored distractor cue arises from observers being able to inhibit the item at that location.

When inhibiting distractors helps: Features

While the evidence for inhibiting features is a bit unclear (further detailed in the "When inhibiting distractors 'hurts'" section below), there are some examples in the literature where having advanced knowledge about distractor features can aid in more efficient visual search. One example of this is recent work by Graves and Egeth (2016). In their paper, they were interested in identifying the

conditions in which *feature search* does or does not allow subjects to avoid attentional capture by salient singletons. The work by Graves and Egeth (2016) was a continuation of the search mode work of Bacon and Egeth (1994) and Leber and Egeth (2006), which proposed that attentional capture by a salient singleton (e.g., a red distractor among green items) varied depending on whether a subject was in *singleton search mode* or *feature search mode*. Subjects are usually in "singleton search mode" when they perform a shape search task where they are told to search for a singleton (i.e., "oddball") shape (e.g., either a square among circles or a circle among squares). Alternatively, subjects are in feature search mode when they are given a specific feature to search for (e.g., search for the square among other shapes). Both Bacon and Egeth (1994) and Leber and Egeth (2006) found that when a salient color singleton was presented in both types of these search displays, only subjects who were in singleton search mode had their attention captured by the irrelevant color singleton. The subjects who received feature search trials were able to ignore the singleton; they showed no additional search time when the salient singleton distractor was present compared to when it was absent. Based on the findings of Bacon and Egeth (1994) and Leber and Egeth (2006), Graves and Egeth (2016) were interested in whether the knowledge about just the target in feature search allowed for subjects to successfully avoid attentional

capture or if knowledge about the salient distractor feature is critical for successful ignoring. In Experiment 1 of their paper they specifically tested this by varying the consistency of the salient distractor color (see Figure 1.6). Specifically, half of the subjects received typical feature search trials (see "Fixed Colors" in Figure 1.6), where in half of the trials all the items are one color (e.g., green) and in the other half of trials one of the items is a different color (e.g., red). All of the items have unique shapes and the subject's task is to locate the circle and report the orientation of a line segment inside. Critically, the other half of subjects received color swapping trials (see bottom of Figure 1.6), where the task was essentially the same except that the majority color and the singleton color swapped randomly across trials so that on half of the trials where the salient singleton was presented it could be a red item among green items or it could be a green item among red items. Graves and Egeth (2016) found that in the typical feature search trials because observers were able to learn that the salient singleton would always be a particular feature (e.g., red) they were able to successfully ignore it and showed no attentional capture when the item was presented or when it was absent. However, in the color-swapping condition the authors found that because the salient singleton was unpredictable subjects were unable to ignore it and thus they showed substantial attentional capture (i.e., longer search times) when the salient singleton was presented compared to

when all the items were one color. Overall, these results suggest that in some situations where attentional capture is possible, knowledge about the color of a salient singleton distractor can help extinguish distraction by that item.

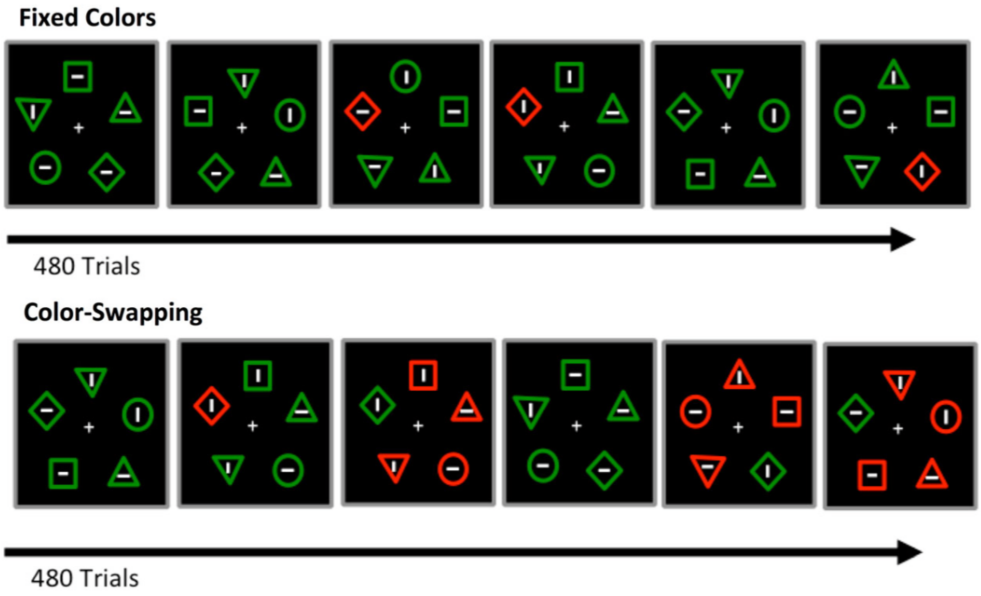

Figure 1.6 A schematic of different feature search trials in Graves and Egeth (2016).

Other evidence suggesting that knowledge about distractor features can aid in more efficient search is from a study by Woodman and Luck (2007). In their study, they had participants perform a working memory task where they were told to hold a color in memory (e.g., red). During the retention period before the participant was tested on the item in memory, they performed a visual search trial. In the visual search trial, the participants were instructed to look for either an upward or downward facing Landolt C, among horizontally facing Landolt Cs.

Critically, they were also instructed that if there happened to be an item in the visual search that matched the color of the item they had in memory, it would always be a distractor. Woodman and Luck (2007) found that when there was an item in the visual search that matched the item in memory, the participants were able to respond faster on those trials compared to trials where there was no item that matched. The authors argue that this allowed for the subjects to avoid attending to the item by creating a "template for rejection" based on the contents of working memory. However, as I will discuss further below, it could have also been the case that observers did in fact attend to the to-be-ignored item, they were able to just rapidly reject it which allowed for more efficient search times on those trials. Alternatively, it could have been the case that because on every trial they provided participants with a working memory item that they could possibly ignore in the search, that for trials where there was no search distractor that matched the contents of working memory the participants would search until they realized that item was not present, thus making those trials appear longer.

To further elucidate the role that active ignoring of distractor features can play in visual search, Arita et al. (2012) conducted a follow up study looking at how explicit ignoring cues would influence search. In their experiments, all trials were

similar in their setup (see Figure 1.7). Specifically, they presented participants with a colored square cue above fixation prior to the onset of a visual search display. There were three cue conditions that were counterbalanced across blocks: positive, neutral, and negative. For the positive cue block, participants were instructed that the cued color would be the color of the target in the upcoming search display. For the negative cued block, they were instructed that they should ignore that color because the target would never appear in the cued color. Finally, in the neutral cued block the color of the cue never appeared in the search display. After the cue presentation, participants were shown the visual search display where they were instructed to look for a Landolt C which was facing upward or downward. Critically, half of the items in one hemifield were one color and half of the items in the other hemifield were another color (see Figure 1.7). The results revealed that both the positive cue and the negative cue lead to significantly faster search times compared to the neutral cue. Additionally, the positive cue lead to faster times compared to the negative cue. The authors took these results to suggest that attentional templates can be used for both guiding attention to an item but also away from an item. However, there is an alternative explanation for their findings (see Becker, Hemsteger, and Peltier (2015) and Beck and Hollingworth (2015)). In their search displays the cued color always occupied one half of the screen.

Therefore, in the to-be-ignored condition it could have been the case that once observers saw the search display, they did in fact utilize the color and spatial mapping to create a positive attentional template. This theory is in line with their results because in the neutral condition observers would still have to search through all items until they found the target, thus making that search slow and inefficient. Additionally, the positive cue condition is still the fastest because observers are able to directly utilized the positive template created from the cue

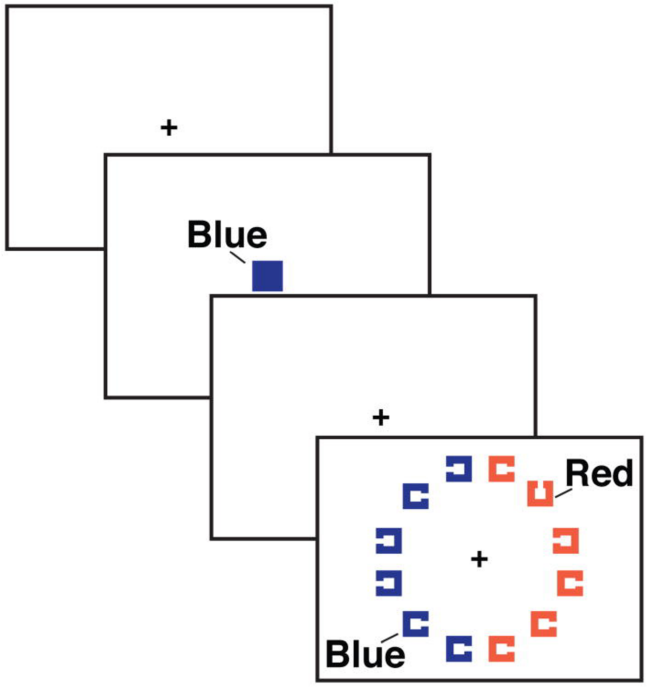

Figure 1.7 An example of an ignore trial in Arita, Carlisle, and Woodman (2012).

itself, identify the relevant side and begin to search through those items for the target. A recent follow-up by Beck and Hollingworth (2015) directly investigated this strategy with a very simple manipulation. Specifically, they had a very similar setup to the previous study by Arita et al. (2012) with a critical change: they

randomly intermixed the location of all the items so that pa rticipants couldn't group the items by hemifield. Their results revealed that while the positive cue still revealed a search benefit compared to the neutral cue, the negative cue resulted in similar search times compared to the neutral cue. Therefore, it appears that the search benefit from directly utilizing to-be-ignored feature information remains unclear.

When Inhibiting Distractors "hurts"

The section above detailed some evidence where having prior knowledge about to-be-ignored distractors can lead to more efficient search. However, there are a number of studies in the inhibition literature that demonstrate the cost of trying to utilize prior knowledge about distractors. Below is a brief review of the literature that claims that utilizing specific to-be-ignored information is costly and inefficient.

When inhibiting distractors hurts: Objects

The findings of Friedman-Hill and Wolfe (1995) are in direct contrast with some of the results detailed above (Arita et al., 2012; Woodman & Luck, 2007) that suggest that prior knowledge about to-be-ignored features can aid in more efficient visual search. Specifically, Friedman-Hill and Wolfe (1995) demonstrated

that an attentional template of to-be-ignored information is not possible in conjunction search. To accomplish this, in one of their experiments they presented observers with a conjunction search task where they needed to find an oddly oriented line. Across four trial types they provided participants with advance knowledge about the color of the target, but not orientation information. In their critical inhibitory condition, they told subjects that the color of the target would not be a certain color (e.g., green). The display contained items that were red, green, yellow, and blue. The oddly oriented line would appear in one of the colors that was not the to-be-ignored color. The authors found that even though they gave participants valid information about what the target would not look like, this condition showed considerably slower search slopes compared to conditions where they provided the color of the target and a pop out orientation search condition.

The work of Friedman-Hill and Wolfe (1995) was not the first example of the cost of inhibitory attentional strategies. About a decade earlier, work by Wegner, Schneider, Carter, and White (1987) demonstrated similar effects, but in the domain of thought suppression. The initial motivation for the work by Wegner et al. (1987) goes back more than a hundred years to the writings of Fyodor Dostoyevsky. In Dostoyevsky's *Winter Notes on Summer Impressions*, he writes

about a memory from his childhood where he challenged his brother to: "try to pose for yourself this task: not to think of a polar bear, and you will see that the cursed thing will come to mind every minute." While the thought experiment is interesting, and you can try it for yourself now, Wegner et al. (1987) were interested in whether actively inhibiting any thought was just as hard as not thinking about a white bear. To provide empirical evidence on this topic, they had 34 participants perform a stream of consciousness task with two conditions: (1) a suppression condition and (2) an expression condition. In the suppression condition, they were instructed to verbalize anything that comes to mind, but to "try not to think of a white bear." In the expression condition, they were told to verbalize anything that comes to mind but to try *to* think of a white bear. All of the participant's verbalizations were recorded individually and they were all told to ring a bell anytime they thought about a white bear in either task. They randomized the order of conditions across participants, such that half received the suppression condition first and the other half received the expression condition. The results revealed that unsurprisingly people in the expression condition rang the bell considerably more than people in the suppression condition. However, people in the suppression condition still produced a large number of bell rings. Furthermore, the critical test is to look at the interaction of the two conditions and whether there was an order effect. They found that

participants who first received the suppression condition demonstrated significantly more bell rings in their following expression condition, compared to those who received the expression condition first. These results suggest that the mere act of trying to ignore a thought, makes that thought more readily available when trying to recall it. Taken together, these results hint at the notion that when we try to actively ignore something, we can't help but obsess over it in our minds.

When inhibiting distractors hurts: Locations

The research detailed in the section above provides some evidence that having prior knowledge about to-be-ignored items can lead to major distracting effects. In contrast, other prior work (Munneke et al., 2008; Ruff & Driver, 2006; Van der Stigchel & Theeuwes, 2006) would suggest that prior knowledge about the location of an upcoming distractor can help search. However, there are some examples in the literature where prior knowledge about a to-be-ignored distractor location can, in fact, hurt search performance. Building on the previous findings of Wegner et al. (1987), Tsal and Makovski (2006) were interested in understanding the interaction of the white bear effect and the stages of distractor processing. Specifically, subjects are eventually able to respond to the target stimulus in these experiments, so the distractor must have

eventually been inhibited? But did that occur? Are they simply unattended, are they ignored from the start, or are they attended prior to being ignored, which is what the white bear effect would suggest. On each trial of their experiment they presented a centrally fixated target with diagonal flanker distractors on each side. On a given trial, the distractor flankers could appear in two configurations: (1) one in the top left and one in the bottom right or (2) one in the top right and one in the bottom left. To give participants knowledge about a to-be-ignored distractor, they had fixed and random blocks. In the fixed blocks, the position where the distractors would appear remained consistent throughout the block (e.g., for all trials the distractors were in the top left and bottom right). In the random blocks the positions changed from trial to trial. Therefore, in the fixed blocks participants knew what locations they should ignore and where they should attend (i.e., the center stimulus). Critically, on some trials they presented two dots: one on an expected distractor location and one on an expected empty location (e.g., if a expected distractor location was the diagonal upper left, there would be a dot there and a dot horizontal from it in the expected empty location in the diagonal upper right). Participants were told to report which dot they perceived first (e.g., left or right). The authors found that when they probed the location of an expected distractor location, observers perceived the dot expected distractor location occurred before the dot in the expected

empty location. These results suggest that the participant's attention was at the to-be-ignored location prior to attending to the target; which is what would be predicted by the white bear effect. Therefore, despite the fact that the participants were encouraged to ignore the flankers because they are distracting, Tsal and Makovski (2006) found that participants actively attended to those to-be-ignored locations.

When inhibiting distractors hurts: Features

Not only is there evidence suggesting conflicting findings of the cost and benefits of utilizing to-be-ignored location information, but there are similarly conflicting findings in work on ignoring to-be-ignored distractor features. Specifically, Moher and Egeth (2012) were interested in investigating whether the benefit of having advance knowledge about a to-be-ignored distractor location found in Munneke et al. (2008) would similarly work if participants had advanced knowledge about to-be-ignored distractor features. To investigate this question, they used a similar paradigm to Munneke et al. (2008). Specifically, in one of their experiments they had two kinds of trials: ignore trials and neutral trials. For ignore trials they presented participants with an explicit word cue (e.g., "Ignore Red") that indicated the color of an upcoming to-be-ignored distractor. This to-be-ignored feature cue changed randomly from trial to trial,

such that on one trial you might be told to ignore red and the next trial you might be told to ignore blue. On neutral trials, they presented a neutral word cue (i.e., "Neutral"). The cues were always 100% valid. Following the presentation of the cue, the search display was shown. In their search displays they presented letters at four locations. The target could either be a capital letter "B" or "F". Additionally, one of the distractor letters was always either a congruent or incongruent lowercase letter (e.g., if the target was a "B", then a congruent distractor would be a "b" and an incongruent distractor would be a "f"). On ignore trials this critical distractor was always the color of the to-be-ignored feature, while on neutral trials the color of this distractor was randomly chosen. Finally, the other two distractors in each display were randomly chosen as either a lowercase or uppercase "K" and "X". The results of Moher and Egeth (2012) were surprising, despite using a very similar paradigm to Munneke et al. (2008), they found the opposite finding: providing participants with explicit to-be-ignored feature information considerably slowed their search, compared to being given no information at all. They go on to demonstrate through additional experiments that it appears that when subjects are given prior knowledge about a to-be-ignored feature, they first attend to that to-be-ignored distractor, inhibit it, and then proceed to look for the target. This initial attention to that to-be-

ignored item, and subsequent rejection, seems to be increasing the "cost" of inhibition.

The Current Study: Goals

In our daily lives, both visual and memory search play a critical role. From finding where our next meeting is, to trying to remember the name of that website a friend told you about, we are constantly searching for a particular item or items. Scaling this up, search plays a critical role in many high-stress professions such as airport baggage screening and medical image screening. These searches often involve identifying important information from memory (e.g., what does a cancerous nodule look like) and using that memory as an attentional search template. Understanding the role that experience/prior knowledge plays in both high- and low-level cognition is critical to understanding the human attentional system and how to improve general search performance.

Much of psychological research on visual search, and more specifically the attentional mechanisms involved in visual search, has focused on how individuals find a target item amongst the clutter of non-target items. However, when our goal is to search for a specific item (e.g., that notebook where we wrote down a Nobel-prize worthy idea), we are also cognizant of what *not* to look for (e.g.,

non-notebook features). The goal of the present research is to understand the role that inhibitory mechanisms play in attention. More specifically, while there is work investigating when inhibitory processes might be involved in search (e.g., Moher & Egeth, 2012; Moher et al., 2014), there is much less work investigating how prior knowledge, or *learning*, interacts with these inhibitory mechanisms.

In the present work, we aimed to understand both the cognitive and neural underpinnings of learning to ignore. Previous research has demonstrated that the consistency of mapping of stimuli onto responses can influence search (e.g., Leber & Egeth, 2006; Graves & Egeth, 2016; Shiffrin & Schneider, 1977; Vatterott & Vecera, 2012; Zehetleitner, Goschy, & Müller, 2012), therefore investigating the critical role that learning plays in inhibitory processes seems an especially promising avenue for investigation. Specifically, we were interested in two distinct types of inhibitory processes that are involved in visual search: (1) the use of explicit to-be-ignored information to guide attention away from non-target information and (2) the role of inhibitory processes in early feature-based attention.

In Chapter 2, we investigated the role that learning plays in visual search when explicit to-be-ignored information about distractor features is provided. Previous

work from Munneke et al. (2008) demonstrated a large benefit in search times when participants were provided with an explicit to-be-ignored location cue. However, when participants were given an explicit to-be-ignored *feature cue* (Moher & Egeth, 2012), past work demonstrated that this information actually hurt rather than helped search times. The current work examined whether having a to-be-ignored feature cue is always costly, or whether learning to ignore consistent to-be-ignored information can eventually speed search.

In Chapter 3, we investigated the role of inhibitory processes in early feature-based attention. Specifically, attention can rapidly (within ~100 milliseconds) influence how incoming visual information is processed. Information about task-relevant features plays a critical role in this modulation and it has been shown that inhibition of distractor information, rather than excitation of target information, drives early feature-based attention. However, the generality of that mechanism has yet to be explored. While past work has demonstrated that inhibition of distractor information can drive feature-based attention, those experiments utilized stimuli in which there was only a single target feature and a single non-target feature. This scenario is far removed from everyday life where a target may appear in a heterogeneous background in which more than one feature may be irrelevant. Here we move one step closer to everyday life by

investigating whether early feature-based attention is facilitated by suppression of distractor feature information when multiple (here, two) distractor features are simultaneously present. Note: I will refer to this experiment from here out as the *two simultaneous distractor* (TSD) paradigm.

Additionally, in past work and in the TSD paradigm above, it has been demonstrated that inhibition of distractor information drives early feature-based attention, when participants were provided with *consistent* to-be-ignored feature information and consistent target feature information throughout a given participants experience (i.e., the target color was red and to-be-ignored distractor features were the colors blue and green for a given participant). The an additional new paradigm, I also investigated whether the consistency of this information is what facilitated inhibition driving early feature-based information (i.e., participants were learning to ignore the consistent to-be-ignored information). Critically, we investigate situations where learning to-be-ignored information would not be possible by presenting subjects with a consistent target feature (e.g., the color red) and multiple distractor features that varied from trial to trial (e.g., any of the following colors could be distractor features: blue, green, orange, yellow, purple). I examined whether inhibition still drives early feature-based attention when observers were faced with such

inconsistency. Note: I will refer to this experiment from here out as the *multiple varying distractor* (MVD) paradigm.

In Chapter 4, I investigated how attention is shaped by experiences, both lived and biologically driven. Our perception of food, for example, is influenced not only by our own lived experiences but also by our evolutionary biology. From the moment we are born, we have some expert knowledge about food. Specifically, inborn preference for palatable energy-dense food is thought to be an evolutionary adaptation that is maladaptive in the modern environment of plenty and contributes to the current obesity epidemic. On the other hand, rewarding local experiences with energy-dense food also seems to stoke our desire to identify and consume these items. One way to investigate the interplay of these two types of experiences is to understand how food preferences influence the control of visual attention. To investigate the role that dietary learning plays in distraction by energy-dense foods, I developed a novel distraction paradigm which borrowed elements from Forster & Lavie, (2011). We use that paradigm across several experiments to investigate the cognitive underpinnings of distraction by energy-dense foods.

In Chapter 5, I investigated one of the electroencephalographic markers (i.e., the N2pc) that is utilized in many attention experiments and attempt to demonstrate that it has been misrepresented. Specifically, in recent years there have been numerous studies that use event-related potentials (ERPs) to understand the structure of specific attentional events that are difficult to probe with only behavioral techniques. The N2pc is one ERP component that has become a common measure for cognitive neuroscientists to establish attentional selection in a variety of experiments. Since the classic study of Woodman and Luck (1999), this component is typically considered to represent the neural marker for shifts of spatial attention across space. However, in this chapter I demonstrate that that the N2pc cannot reflect just an initial shift of attention, but in fact it reflects (1) post-selection processing well beyond the initial shift of attention or (2) post-selection processing plus the initial shift of attention. I discuss how these findings are supported by other neurological evidence and how a reframing of the N2pc as a marker of post-selection processing fits within the ERP framework of other attentional components (e.g., the Pd).

In Chapter 6 (General Discussion), I summarize my results drawing key findings and similarities across several experiments. Furthermore, I address how these

findings fit within the larger framework of attention. I do this by describing how my findings could inform current models of attention (e.g., Biased Competition, Guided Search). Finally, I end the chapter with a few concluding remarks.

Chapter 2: The Costs and Benefits of Learning to Ignore

Chapter 2: Synopsis of Completed Experiments

When we search a visual scene, we generally have information about what we are aiming to find and this aids in our ability to quickly identify the target of our search. For example, when a radiologist searches for a tumor, they have knowledge about what the tumor should and should not look like, or where it could and could not appear. However, does having information about what to not look for, or *ignore*, provide any benefit in search? Previous work demonstrates that when participants were given an explicit to-be-ignored *feature cue* (Moher & Egeth, 2012), this information actually hurt rather than helped search times. The current experiments examined whether having a to-be-ignored feature cue is always costly, or whether learning to ignore consistent to-be-ignored information can eventually speed search. I report a novel finding that allowing observers to learn to ignore non-target feature information hastens visual search for a target item. The experiments in this part of the chapter have been published in *Psychological Science* (Cunningham & Egeth, 2016).

Title: Taming the White Bear: Initial Costs and Eventual Benefits of Distractor Inhibition
Accepted at Psychological Science

Abstract

Previous research indicates that prior information about a target feature, such as its color, can speed search. Can search also be speeded by knowing what a target will not look like? In the two experiments reported here, participants searched for target letters. Prior to viewing search displays, participants were prompted either with the color in which one or more nontarget letters would appear (ignore trials) or with no information about the search display (neutral trials). Critically, when participants were given one consistent color to ignore for the duration of the experiment, compared with when they were given no information, there was a cost in reaction time (RT) early in the experiment. However, after extended practice, RTs on ignore trials were significantly faster than RTs on neutral trials, which provides a novel demonstration that knowledge about nontargets can improve search performance for targets. When the to-be-ignored color changed from trial to trial, no RT benefit was observed.

Introduction

When people visually search for a target item (e.g., a set of car keys), they are often faced with a large amount of clutter (i.e., nontarget items). In the case of car keys, the search is fairly easy because people have a representation of what the target should look like; therefore, they will search until they find an object that matches the target. However, during some visual searches, they might instead have information about what the target might not look like. Intuitively, knowing what not to look for— what to ignore—should reduce the number of items that need to be considered, thus reducing search times. Does knowing what feature to ignore prove, in fact, to be a benefit in visual search?

Prior work has suggested the surprising possibility that even when subjects are given valid feature information about to-be-ignored items (e.g., color), it actually hurts rather than helps their performance (e.g. Moher & Egeth, 2012; Tsal & Makovski, 2006). There is a family resemblance between these results and the "white bear" effect (Wegner, Schneider, Carter, & White, 1987). In an experiment by Moher and Egeth (2012), when observers were given nontarget feature information (in the form of a pre-trial cue) on a trial-by-trial basis, reaction times (RTs) were slower than when they were given no information at all. Moher and Egeth suggested that this was because, in their search process,

observers first selected the to-be-ignored item and then inhibited it. In a follow-up experiment, Moher and Egeth (2012) included a probe-dot detection task on a subset of trials. They found that when observers were given to-be-ignored information, they were faster at detecting a probe dot at the location of the to-be-ignored distractor when it was presented early in the trial (117 ms) compared with later in the trial (167 ms). It seems that observers in Moher and Egeth's experiment selected the to-be-ignored item and subsequently rejected it. Thus, observers were unable to preattentively reject to-be-ignored information; that is, participants failed to create a "template for rejection" (e.g., Arita, Carlisle, & Woodman, 2012; Woodman & Luck, 2007).

In contrast to the foregoing, Moher, Lakshmanan, Egeth, and Ewen (2014) demonstrated that when target and distractor information were held constant for the duration of the experiment, observers appeared to attenuate processing of distractor features rather than boost processing of target features. This work suggests that a template for rejection can be created when dealing with to-be-ignored information. However, it is not yet clear what drives the creation of such a template. A possible explanation for these conflicting results may be that successful ignoring of task-irrelevant distractor information is something that needs to be learned.

We consider here the possibility that creation of a template for rejection is facilitated by extended experience with a consistently ignored feature. This possibility is supported by the difference in methods of two previous studies (i.e., Moher & Egeth, 2012; Moher et al., 2014) and the striking difference in their outcomes. In the first study (Moher & Egeth, 2012), the to-be-ignored feature changed on a trial-by-trial basis, whereas in the second study (Moher et al., 2014), the to-be-ignored feature remained fixed for an entire experimental session. There were, of course, other differences between these studies, but the difference in consistency of mapping of stimuli onto responses seems an especially promising avenue for investigation in light of previous work on the topic (e.g., Shiffrin & Schneider, 1977; Vatterott & Vecera, 2012; Zehetleitner, Goschy, & Müller, 2012).

To examine this possibility, we conducted two experiments. In Experiment 1, participants completed a visual search task in which they could learn about one particular distractor feature. At the start of each trial, participants were provided with either a cue that provided no information about the upcoming stimulus display (neutral cue) or a cue that instructed them which color in the following stimulus display to ignore (ignore cue). The ignore cue was always valid, that is,

it always referred to a presented distractor. If participants can learn to effectively ignore consistent to-be-ignored features, then over the course of the experiment, we expected them to produce faster RTs on ignore trials than on neutral trials. In Experiment 2, we used the same paradigm as in Experiment 1, but with a larger stimulus array, to minimize the possibility that participants might learn to attend to the other colors rather than try to ignore the to-be-ignored color. Additionally, we were interested in whether participants could learn to ignore the to-be-ignored feature across many items (6 out of 12 items). The paradigms used in both of these studies allowed us to investigate whether consistency in the mapping of to-be-ignored information is critical for developing a template for rejection.

Experiment 1

Method

Participants

A group of 26 Johns Hopkins University undergraduate students and community members (mean age = 20.5 years; 10 male, 16 female) with normal or corrected-to-normal visual acuity and normal color vision participated in the experiment. We conducted a power analysis using G*Power (Faul, Erdfelder, Lang, & Buchner, 2007), which showed that given an *f* of 0.25, 26 participants would be

required to have 85% power to detect the effect in our design (Cohen, 1988, suggests that an effect size of 0.25 indicates a medium-sized effect). Data collection therefore stopped once we reached 26 participants. One subject was eliminated because she had an extremely high error rate (32%; the mean error rate was 4% for the 25 remaining subjects). The participants received extra credit in undergraduate courses or monetary payment as compensation, and all gave informed consent. The Johns Hopkins Homewood Institutional Review Board approved the protocol.

Stimuli

Experimental sessions were carried out on a Dell Precision T-3400 2.33-GHz computer. Stimuli were presented on a Dell 1708 FP monitor. Stimulus presentation and data analysis were performed using programs written in MATLAB and using the PsychToolbox software (Brainard, 1997). The screen had a refresh rate of 60 Hz, and the resolution of the screen was 1,280 × 1,024 pixels.

Stimuli appeared surrounding a central fixation cross that subtended 0.55° of visual angle at a viewing distance of approximately 60 cm. Stimuli consisted of four letters from the English alphabet, which were randomly assigned to appear

in one of four locations (surrounding fixation) at 0°, 90°, 180°, and 270° from vertical. Each letter subtended a visual angle of 0.86°, and the distance between fixation and the closest edge of each letter subtended 4.96° of visual angle.

On each trial, either a capital "B" or "F" was selected randomly to appear as the target letter. Additionally, a lowercase "b" or "f" was selected randomly to appear as one of three distractor letters. The distractor letter on each trial was either compatible with the target letter, meaning that it shared the target's identity (e.g., "B" was the target and "b" the distractor), or incompatible, meaning that it did not share the target's identity (e.g., "F" was the target and "b" the distractor). The compatibility manipulation was included to make our paradigm as similar as possible to those used in previous studies. Specifically, Moher & Egeth (2012) included it in their design because Munneke, Van der Stigchel, & Theeuwes (2008), who examined the ability to ignore cued spatial locations, found an interesting effect of compatibility that was dependent on whether they cued a distractor location. However, Chao (2010) used a similar paradigm and found no significant interaction with cue type and compatibility, and Moher and Egeth (2012) also found that interaction to be not significant. Those failures to replicate Munneke et al.'s results notwithstanding, we included this manipulation to investigate whether learning to ignore a consistently to-be-

ignored color would be affected by the relationship of the target and distractor information. The remaining two distractor letters on every trial were a "k" and an "x," one of which was chosen randomly to be uppercase.

There were two trial types. On neutral trials, the color of each of the four letters was selected randomly without replacement from a set of four colors (red, blue, green, and yellow). However, on ignore trials, the to-be-ignored item always appeared in the to-be-ignored color, while the other three letters were randomly assigned the remaining three colors.

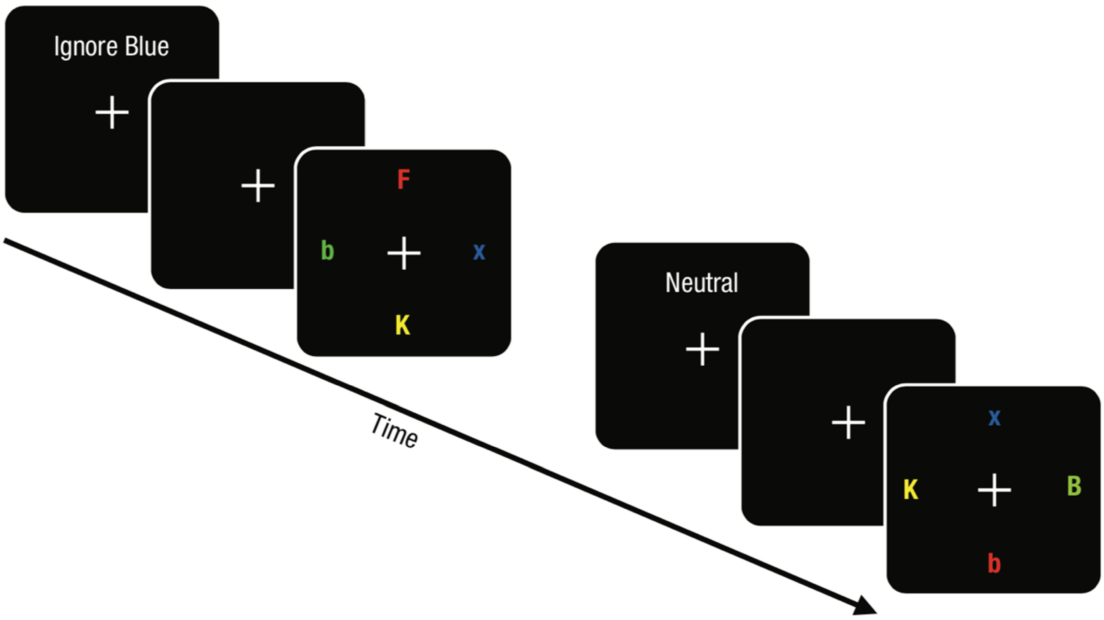

Figure 2.1 Examples of the two trial sequences used in Experiment 1. On ignore trials (left), a cue at the start of the trial told participants which color in the following stimulus array to ignore. On neutral trials (right), the cue gave no stimulus information. On both types of trial, one of the colored letters in the stimulus array was the target ("B" or "F"), which participants had to indicate by pressing a key. Each participant was given a randomly selected color to ignore for the duration of the experiment (the color was counter-balanced across observers). There were 720 trials, half of which were ignore trials and half of which were neutral trials, randomly intermixed.

Design and Procedure

At the beginning of each trial, a cue was presented for 1,000 ms in white letters above the fixation cross (see Fig. 2.1). This cue indicated the trial type. On ignore trials, the name of the color to be ignored was stated in the cue (e.g., "Ignore Red"); on neutral trials, the cue just said "Neutral." These cues subtended 0.57° of visual angle vertically and between 2.86° and 5.92° of visual angle horizontally, and they were always valid. Unlike in previous studies, the color to be ignored remained the same for the entire duration of the experiment. The specific color to be ignored was randomly assigned for each participant. On ignore trials, the letter appearing in the to-be-ignored color was always a distractor. Neutral cues gave the participants no information about the color of the target or nontarget items on the upcoming trial. Because only four colors were used in the experiment, the to-be-ignored color could appear on neutral trials.

After the cue was presented, the fixation cross remained in the center of the screen for 1,000 ms. Then the four letters appeared on the screen and remained until participants responded. The participants were told to indicate whether a capital "B" or "F" was present by pressing the "z" key or "/" key, respectively. They were instructed to respond as quickly and accurately as possible. Following

their response, there was an intertrial interval consisting of a 500-ms blank black screen. No feedback was provided. Participants completed 720 trials total; 50% of the trials were ignore trials, and 50% were neutral trials, randomly intermixed. Experimental sessions lasted 60 to 75 min.

Results

Following the procedure of Moher and Egeth (2012), we removed RTs that were faster than 100 ms and more than 3.5 standard deviations above or below the mean. The latter criterion was based on a modified recursive trimming procedure developed by Selst and Jolicoeur (1994). This resulted in the elimination of 1% of all trials. Additionally, we removed trials with errors from the analysis, which accounted for about 4% of all trials. Mean RTs for all included trials are given in Table 1.1. To analyze the effect of practice (or experience), we grouped the trials into four 180-trial blocks.

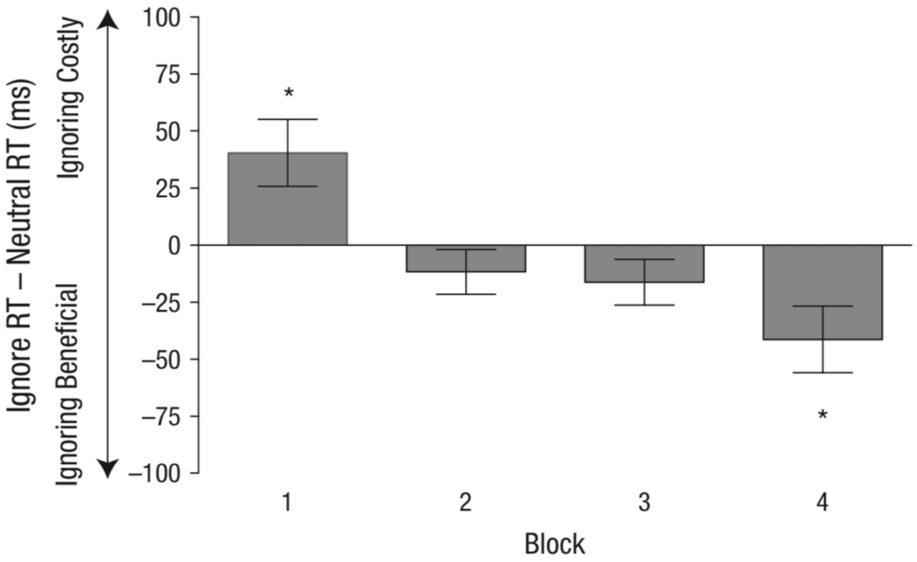

Figure 2.2 Mean difference in reaction time (RT) between ignore and neutral trials in Experiment 1, separately for each block of 180 trials. Asterisks indicate blocks in which RTs for the two trial types were significantly different (*$p < .05$). Error bars show ±1 SEM calculated within-participants using the method of O'Brien and Cousineau (2014).

We included compatible and incompatible trials in a 2 (trial type: ignore vs. neutral) × 2 (compatibility: compatible vs. incompatible) repeated-measures analysis of variance (ANOVA). There was a significant main effect of compatibility, $F(1, 24) = 4.59$, $p < .05$, $\eta_p 2 = .16$, with RTs on incompatible trials (M = 1,011 ms) being slower than RTs on compatible trials (M = 997 ms); however, there was no significant effect of trial type, $F(1, 24) = 0.604$, $p = .445$. Additionally, there was no significant interaction between trial type and compatibility, $F(1, 24) = 0.106$, $p = .75$. These results were similar to those found

by Moher and Egeth (2012) and Chao (2010). Therefore, in our further analyses, we collapsed across compatible trials and incompatible trials.

Table 2.1 Reaction times (in msec) with standard deviations in parentheses for Experiment 1 by block

	Block 1	Block 2	Block 3	Block 4
Ignore	1131 (274)	981(194)	963 (204)	928 (224)
Neutral	1091 (235)	993 (188)	979 (204)	970 (252)

Figure 2.2 shows the mean difference in RT on ignore trials and neutral trials for all participants across all four blocks. We performed a 2 (trial type) × 4 (block) repeated-measures ANOVA on RTs. We found no main effect of trial type, $F(1, 24) = 0.746$, $p = .396$. However, we found a significant main effect of block, $F(3, 72) = 9.871$, $p < .01$, $\eta_p 2 = .3$; RTs decreased over the course of the experiment. Critically, we also found a significant interaction between trial type and block, $F(3, 72) = 5.668$, $p < .01$, $\eta_p^2 = 0.2$. Additional contrasts revealed that this interaction was largely driven by the differences between trial type in Block 1 and trial type in Block 4, $p < .001$, which accounted for approximately 95% of the effect. Finally, analyses of simple main effects revealed that RTs for the ignore cue were significantly slower than RTs for the neutral cue in Block 1, $p <$

.05, and RTs for the ignore cue were significantly faster than RTs for the neutral cue in Block 4, $p < .05$.

The results suggest that when participants ignored the nontarget information, there was a cost in the beginning (Block 1), which is similar to what Moher and Egeth (2012) found. However, as participants learned about the (consistently mapped) to-be-ignored information, they efficiently ignored the nontarget information, which resulted in a benefit in RT (Block 4).

We conducted a further analysis restricted to neutral trials. Given our experimental design, two types of neutral trials were presented. Specifically, because neutral trials used the same four colors (i.e., red, green, blue, yellow) that were used in ignore trials, each neutral trial contained a letter in the color that a participant was learning to ignore. Thus, there were two different types of neutral trial: The target was either (a) the color the participant was learning to ignore or (b) some other color. If participants were learning something about the to-be-ignored color and that this color should not contain the target, then this should have resulted in an RT profile that roughly paralleled the profile observed between neutral and ignore trials.

To investigate this possibility, we performed a 2 (neutral-trial type) × 4 (block) repeated-measures ANOVA on RTs (Fig. 2.3). We found no main effect of neutral-trial type, $F(1, 24) = 0.06$, $p = .809$. However, we did find a significant main effect of block, $F(3, 72) = 3.91$, $p < .05$, $\eta_p 2 = .14$; RTs decreased over the course of the experiment. Critically, there was a significant interaction between neutral-trial type and block, $F(3, 72) = 6.16$, $p < .002$, $\eta_p 2 = .2$. In Block 1, participants were faster when the target on a neutral trial was in the to-be-ignored color. This suggests that at this point, participants were selecting the feature they were starting to learn to ignore on ignore trials, as suggested by the probe-dot-detection results in Moher and Egeth (2012). However, over time (Blocks 2 and 3), this pattern reversed: Participants were slower to select the target on neutral trials when it was the to-be-ignored color on ignore trials. Additionally, in Blocks 2 and 3, RTs on neutral trials were faster when the target was in another color; this suggests that participants were efficiently inhibiting the to-be-ignored color. However, in Block 4, there was no RT difference between the neutral-trial types. It is difficult to know whether this effect was a real reduction in the interference or a reflection of noise in the data; further experiments will be needed to untangle these possibilities. Finally, dropping neutral trials on which the target was the color the participants were learning to

ignore still yielded a significant interaction ($p < .05$) when we compared ignore trials with the remaining neutral trials (similar to the pattern shown in Fig. 2.2).

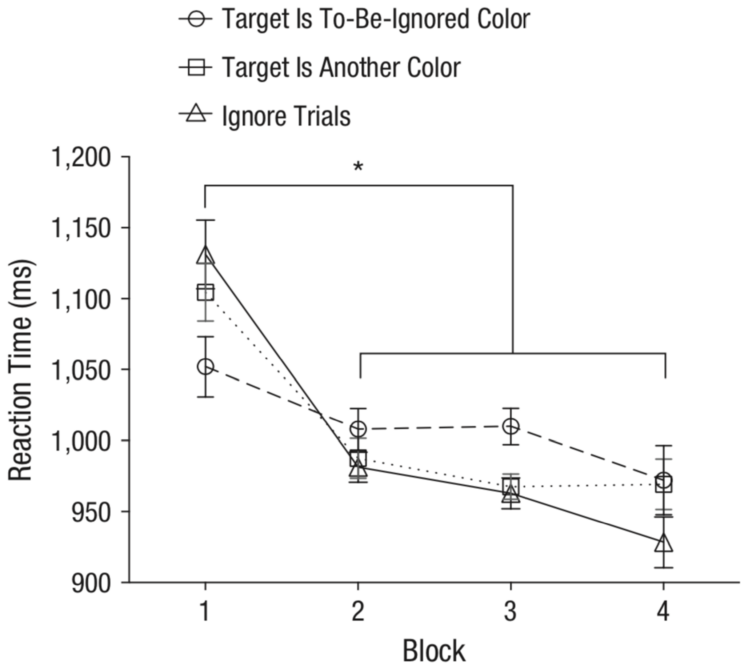

Figure 2.3 Mean reaction time (RT) on the two types of neutral trial in Experiment 1, separately for each block of 180 trials. Neutral trials were separated according to whether the target was in the color that participants had been instructed to ignore on ignore trials or in a different color. RTs for ignore trials are included for comparison purposes. Asterisks indicate significant differences between RTs for each block (*p < .05). Error bars show ±1 SEM calculated within-participants using the method of O'Brien and Cousineau (2014).

Finally, the RT benefit shown in Figure 2.2 could possibly have been driven by the larger number of target-color repetitions (e.g., the target "B" was green on a given trial, and the target "F" was green on the following trial) on ignore trials (average of 30% of trials across all participants) than on neutral trials (average of 25% of trials across all participants).1 The reason for this difference is that

targets on ignore trials could be one of three colors, while targets on neutral trials could be one of four colors. Thus, the number of possible target repetitions was higher for ignore trials. To explore the effect of this imbalance of probabilities, we conducted an additional analysis in which we removed all target-repetition trials. A 2 (trial type) × 4 (block) repeated-measures ANOVA revealed that even when we discounted the possibility that target repetitions facilitated the benefits shown on ignore trials, the results were the same. Specifically, we found no main effect of trial type, $F(1, 24) = 0.512$, $p = .481$. We found a significant main effect of block, $F(3, 72) = 9.311$, $p < .001$, $\eta_p 2 = .28$; RTs decreased over the course of the experiment. Finally, there was still a significant interaction between trial type and block, $F(3, 72) = 5.974$, $p < .01$, $\eta_p 2 = .2$. Therefore, it seems the benefit of learning to ignore a particular color was not facilitated by more target-repetition trials in the ignore condition than in the neutral condition.

Discussion

Experiment 1reveals a surprising result: Inhibiting non-target-feature information can be costly or beneficial depending on how much the participant has learned about the to-be-ignored feature. Furthermore, the cost in RT for ignore trials compared with neutral trials suggests that participants were unable to use a

template for rejection early in practice to facilitate efficient feature inhibition. However, after a few hundred trials of learning to ignore the to-be-ignored feature, participants showed a benefit (i.e., faster RTs). This demonstrates that while participants cannot create a template for rejection immediately, they can after learning to ignore a particular to-be-ignored feature.

Experiment 2

In Experiment 1, we demonstrated that when participants learned to inhibit to-be-ignored feature information, they searched more efficiently, compared with when they were provided with no information. However, some critical questions remain. First, how general are the results from Experiment 1? Specifically, will similar results be obtained under different experimental conditions? Second, do participants learn to ignore the to-be-ignored feature or are they merely learning to attend to the other possible target colors? Finally, do the same effects demonstrated in Experiment 1remain when interference on neutral trials is removed (i.e., if the to-be-ignored color never shows up on neutral trials)?

To address these questions, we conducted two follow-up experiments. In Experiment 2a, participants were provided with a to-be-ignored color cue on ignore trials, but, unlike in Experiment 1, the to-be-ignored information changed

from trial to trial. Additionally, participants viewed a stimulus display somewhat similar to one used by Arita et al. (2012); instead of ignoring 1 item on ignore trials, as in Experiment 1, participants could ignore 6 out of 12 items (i.e., these 6 to-be-ignored items were all in the same color, while the other 6 items were all different from one another and selected from a set of seven colors). Experiment 2b was essentially the same as Experiment 2a, except that the to-be-ignored color remained consistent throughout the experiment.

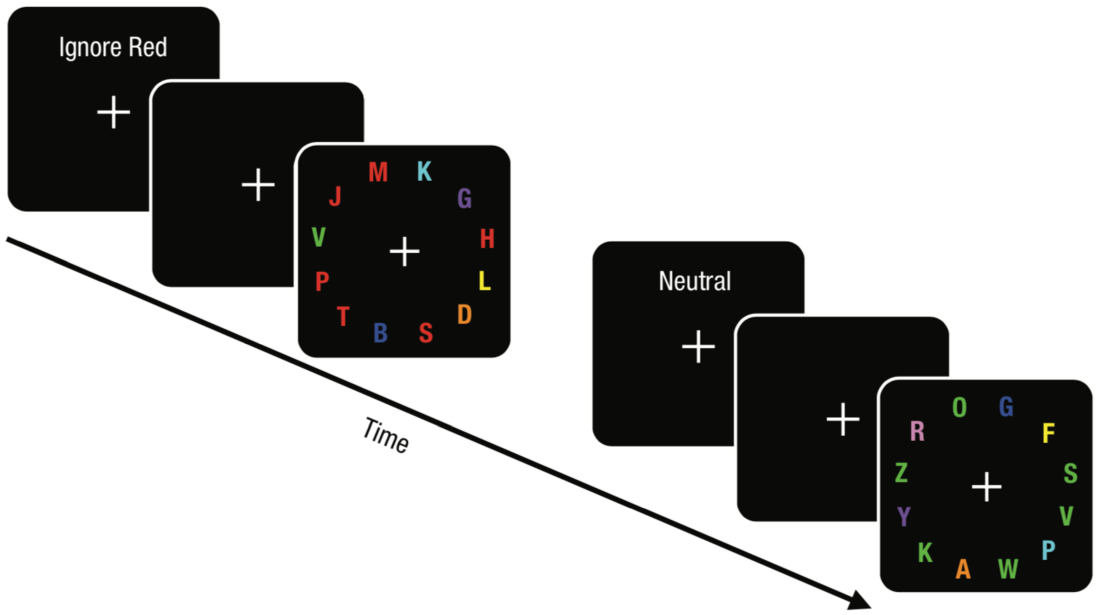

Figure 2.4 Examples of the two trial types, ignore (left) and neutral (right), in Experiments 2a and 2b. Cues gave the same information as in Experiment 1, and participants again searched for a target letter ("B" or "F") in the stimulus display. However, the display in Experiments 2a and 2b consisted of a circular pattern of 12 letters, 6 of which were the same color, whereas the other 6 each were a different color. In Experiment 2a, the to-be-ignored color varied from trial to trial. There were 720 trials, half of which were ignore trials and half of which were neutral trials, randomly intermixed. Crucially, in Experiment 2a, the to-be-ignored color varied from trial to trial, whereas in Experiment 2b, the to-be-ignored color was the same from trial to trial, as in Experiment 1.

Method

Participants

A group of 52 Johns Hopkins University undergraduate students and community members (mean age = 22.9 years; 10 male, 42 female) with normal or corrected-to-normal visual acuity and normal color vision participated in the experiments (26 participants were assigned to each experiment). A power calculation similar to the one used in Experiment 1led us to stop data collection once we reached 26 participants. The participants received extra credit in undergraduate courses or monetary payment as compensation and gave informed consent. The Johns Hopkins Homewood Institutional Review Board approved the protocol.

Stimuli, design, and procedure

Except as noted, the stimuli, design, and procedure were the same as in Experiment 1. The key difference was the number of stimuli and their arrangement in the search displays (see Fig. 2.4). Stimuli consisted of 12 capital letters from the English alphabet displayed around a central fixation cross. Each letter was randomly assigned to appear in 1 of 12 locations, and the 12 letters were equally spaced on the circumference of an imaginary circle. The distance between fixation and the closest edge of each letter subtended 5.5° of visual angle. As in Experiment 1, either a "B" or an "F" was selected randomly as the

target letter on every trial. Additionally, 11 other uppercase letters were selected as the nontarget items. Nontarget letters were chosen from the other 24 letters from the English alphabet. Eight colors were used: red, blue, green, yellow, pink, purple, orange, and aqua.

On neutral trials, six letters were selected randomly to appear in the same color (we refer to this as the majority color). The other six letters each appeared in a different color, which was selected randomly without replacement. The spatial location of all colored letters was randomly selected so that stimuli would not be grouped by color. On neutral trials for both Experiments 2a and 2b, the target letter could appear randomly either in the majority color or as any of the other colors. Thus, a color cue was not informative on neutral trials.

On ignore trials, the to-be-ignored color was always the majority color. Additionally, the target was never in the to-be-ignored color; rather, it was always one of the heterogeneously colored letters (see Fig. 2.4). Therefore, participants could benefit from the to-be-ignored information by knowing that the target was not the to-be-ignored color, thus they could attempt to ignore 6 out of 12 items. Critically, in Experiment 2a, the to-be-ignored color varied from trial to trial; thus, the participant could not learn anything consistent about the to-be-ignored information. However, in Experiment 2b, the to-be-ignored

information was held constant for the entire experiment (e.g., a participant could ignore red on all ignore trials). The specific to-be-ignored color was randomly assigned for each participant. As on neutral trials, the spatial location of all colored letters was randomly selected so that stimuli would not be grouped by color. Participants completed 720 trials total, 50% of the trials were ignore trials and 50% neutral trials, randomly intermixed. Experimental sessions lasted 60 to 75 min

Results

For Experiments 2a and 2b, we removed responses that were faster than 100 ms and more than 3.5 standard deviations above or below the mean. This resulted in the elimination of 1% of all trials for each experiment. Additionally, we removed all trials with errors from the analysis, which accounted for approximately 3% of all trials for each experiment. Finally, to analyze the effect of condition across the duration of the experiments, we divided the trials into ten 72-trial blocks. Mean RTs for all included trials are given in Table 2.2.

For both experiments, we calculated a mean difference score by subtracting the RT on neutral trials from the RT on ignore trials (see Fig. 2.5). This was done for

each participant for each block. Although we present a difference score in Figure 2.5 for clarity, all analyses were conducted on raw RTs.

We first ran a 2 (trial type) × 10 (block) repeated-measures ANOVA for Experiment 2a. We found no significant effect of trial type, $F(1, 25) = 0.006$, $p = .939$, and no significant interaction of trial type and block, $F(9, 225) = 1.555$, $p = .13$. Therefore, it does not appear that participants acquired a template for rejection, contrary to the findings of Arita et al. (2012). However, as Beck and Hollingworth (2015) point out, the inhibitory benefit found by Arita et al. (2012) was very likely supported by the fact that participants could rely on a simple spatial template. This was because all of the to-be-ignored items in their study were grouped in one hemifield, while the other items were located in the opposite hemifield. Therefore, it seems that when to-be-ignored information is variable (and stimuli are not grouped by color), participants have a difficult time developing a beneficial template for rejection.

In contrast, in Experiment 2b, we found a significant benefit of learning about the to-be-ignored color, similar to the findings in Experiment 1. While there was a significantly greater RT cost in Block 1 on ignore trials than on neutral trials,

participants were able to learn to successfully ignore the to-be-ignored color, which resulted in a greater RT benefit on ignore trials than on neutral trials in Blocks 2 through 10 (see Fig. 2.5). A 2 × 10 repeated-measures ANOVA revealed a significant effect of trial type, $F(1, 25) = 36.821$, $p < .001$, $\eta_p 2 = .6$, and a significant interaction of trial type and block, $F(9, 225) = 3.235$, $p < .01$, $\eta_p 2 = .12$. Furthermore, we conducted a 2 (experiment) × 2 (trial type) × 10 (block) three-way ANOVA, in which we found that the interaction in Experiment 2b was significantly different from the interaction in Experiment 2a, $F(9, 450) = 2.106$, $p < .05$, $\eta_p 2 = .04$.

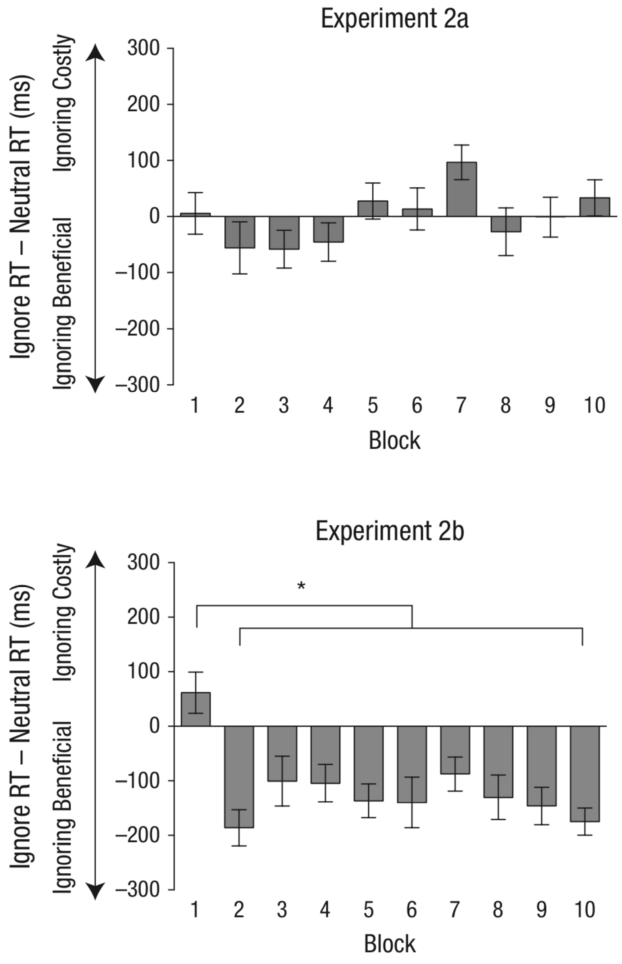

Figure 2.5 Mean difference in reaction time (RT) between ignore and neutral trials in Experiments 2a and 2b, separately for each block of 72 trials. Asterisks indicate significant differences between RTs for each block (*$p < .05$). Error bars show ±1 SEM calculated within-participants using the method of O'Brien and Cousineau (2014).

Additionally, we examined whether target-color repetitions (e.g., the target "B" is green on a given trial, and the target "F" is green on the following trial) played a role in the benefit of learning to ignore. Recall that in Experiment 1, we found that the learning-to-ignore benefit was not facilitated by more target-repetition trials in the ignore condition than in the neutral condition. In

Experiment 2b (in which participants learned a to-be-ignored color), there were a similar number of target-repetition trials in ignore trials and neutral trials (average of 14% of trials across all participants) because of the large number of colors available in both tasks. However, we still examined whether the benefit of learning to ignore was facilitated by target repetitions. Specifically, we conducted a 2 (trial type) × 10 (block) repeated-measures ANOVA in which we removed all target-repetition trials for Experiment 2b (in which participants received consistent to-be-ignored cues). This analysis revealed that, again, even when we removed the possibility that target repetitions were facilitating the benefit shown on ignore trials, the same results were seen. Specifically, we found a main effect of trial type, $F(1, 25) = 44.645$, $p < .01$, $\eta_p 2 = .641$. We also found a significant main effect of block, $F(9, 225) = 5.819$, $p < .01$, $\eta_p 2 = .189$; RTs decreased over the course of the experiment. Finally, we found that there was still a significant interaction between trial type and block, $F(9, 225) = 2.621$, $p < .05$, $\eta_p 2 = .1$. Therefore, it seems that the learning-to-ignore benefit was not facilitated by target repetitions, which mirrors the results of Experiment 1.

We also found an interesting interaction between target repetitions (target repetition vs. no target repetition) and trial type (ignore vs. neutral). Target repetitions speeded search for neutral trials—RT was longer on trials without

target repetition (M = 1,770 ms) than on trials with target repetition (M = 1,738 ms). However, the opposite was true for ignore trials—RT was shorter on trials without target repetition (M = 1,642 ms) than on trials with target repetition (M = 1,696 ms). We ran a 2 (target repetition) × 2 (trial type) repeated-measures ANOVA and found a significant main effect of trial type, $F(1, 25) = 13.2$, $p < .05$, $\eta_p 2 = .35$, but no significant effect of target repetition, $F(1, 25) = 0.617$, $p = .440$. We found a significant interaction between trial type and target repetition, $F(1, 25) = 6.753$, $p < .05$, $\eta_p 2 = .213$. These results suggest that while target repetitions benefitted participants on neutral trials (as is normally the case), they actually hindered participants on ignore trials. Perhaps because participants were learning to ignore a specific feature, anything conflicting with that information in visual working memory resulted in interference. Therefore, not only did target repetitions not facilitate the learning-to-ignore RT benefit that we demonstrated, but also they seemed to interfere with search on those trials.

Table 2.2 Reaction times (in msec) with standard deviations for Experiment 2 by block

	Experiment 2a: Varied to-be-ignored cues		Experiment 2b: Consistent to-be-ignored cues	
	Ignore	Neutral	Ignore	Neutral
Block 1	1971 (457)	1965 (529)	1989 (451)	1927 (434)
Block 2	1813 (491)	1869 (541)	1723 (346)	1909 (437)
Block 3	1761 (532)	1819 (507)	1632 (419)	1733 (486)
Block 4	1748 (577)	1793 (595)	1623 (555)	1727 (476)
Block 5	1736 (427)	1708 (457)	1552 (358)	1688 (432)
Block 6	1737 (438)	1724 (450)	1577 (356)	1716 (512)
Block 7	1723 (443)	1627 (361)	1596 (403)	1683 (349)
Block 8	1678 (475)	1705 (435)	1670 (694)	1801 (681)
Block 9	1649 (528)	1651 (490)	1595 (464)	1741 (484)
Block 10	1659 (563)	1626 (538)	1573 (426)	1748 (518)

Discussion

In Experiments 2a and 2b, we replicated and extended the results of Experiment 1by demonstrating with rather different displays that participants can learn to ignore specified feature information. Additionally, in Experiment 2b, the RT benefit on ignore trials appeared more quickly than in Experiment 1. Because the displays in Experiments 1 and 2b were not identical, we cannot make strong statements about the learning rates in both experiments. Nevertheless, it does seem notable that evidence of a significant ignoring benefit was evident after just 72 trials in Experiment 2b, while in Experiment 1such a benefit was not evident until near the end of the session, even though many more colors were used in Experiment 2b (eight) than in Experiment 1(four).

Additionally, Arita et al. (2012) found that the benefit of top-down cues was much greater for larger visual-set sizes than for smaller visual-set sizes. For the current experiments, participants in Experiment 1could ignore 1 out of 4 items initially, while participants in Experiment 2 could ignore 6 out of 12 items initially. Therefore, the rapid emergence of the ignoring benefit in Experiment 2b is likely a function of the number of items that participants could ignore.

If participants were learning to attend to the other colors rather than learning to inhibit the to-be-ignored color, then learning should have been more difficult in Experiment 2b. Chao (2010), using similar displays to those we used in Experiment 1, explicitly compared a condition in which one location was cued to be ignored with a condition in which the other three locations were cued to be attended. When three possible locations were precued, participants could not use this information to improve target detection. Allen and Humphreys (2007) found similar results using a preview search task, in which a number of distractors is presented before the onset of the rest of the search display. Finally, in our Experiment 2b, eight colors were used, which is well beyond the capacity of visual working memory (e.g. Cowan, 2010).

General Discussion

The current study provides a novel demonstration that knowledge about nontargets can improve search performance. Across two experiments, we presented evidence that learning to ignore to-be-ignored information can result in a benefit that is modulated by participants' time spent learning about the to-be ignored feature. Additionally, the present study goes beyond previous research by demonstrating that the benefits of learning to ignore consistent distractor information are not only influenced by time spent learning, but also they are affected by the utility of that information. In Experiment 1after a few hundred trials, participants clearly showed an RT benefit. We compared the time course of learning in Experiment 1 to Experiment 2, where participants could ignore multiple items in the display rather than just one item, and found that the benefit of learning to ignore emerged after only 72 trials. Results from Experiment 2 demonstrated that, within the same task, participants benefited only from to-be-ignored cues when those cues were consistent, which allowed participants to learn to ignore them. Overall, the current study presents new evidence detailing the circumstances in which negative cuing of distractors can facilitate the speed of visual search.

The current results are supported by a number of previous studies demonstrating the benefit of attentional sets that develop with sufficient

learning (Cosman & Vecera, 2014; Gal et al., 2009; Geng, 2014; Moher, Lakshmanan, Egeth, & Ewen, 2014; Zehetleitner, Goschy, & Müller, 2012). On the face of it, it might look like the present design—with its explicit verbal instructions—resulted in explicit learning of an attentional set. However, it is difficult to argue that no form of implicit learning occurred. Previous research has shown that observers are very sensitive to statistical regularities in visual search displays (e.g., Turk-Browne, Jungé, & Scholl, 2005). It would be interesting in further research to compare the efficacy of explicit and implicit learning in the acquisition of an attentional set to ignore a specific feature.

The present experiments demonstrate circumstances in which the benefit of distractor inhibition arises from consistent learning; however, the specific attentional mechanisms that support such behavior have yet to be determined. Belopolsky, Schreij, & Theeuwes (2010) demonstrated in a series of attentional-capture experiments that top-down goals (e.g., "find the square") do not result in the filtering out of irrelevant salient objects. Rather, they demonstrated that participants will still select salient irrelevant stimuli, but they will subsequently rapidly disengage from those stimuli that do not match the top-down goal (e.g., a bright red triangle). It seems possible that participants in the present study utilized a similar mechanism.

Although the rapid-disengagement hypothesis is not universally accepted (e.g., Chen & Mordkoff, 2007; Eimer & Kiss, 2008; Folk & Remington, 2006; McDonald, Green, Jannati, & DiLollo 2013), it should be noted that the context for all of these critiques is attentional capture by salient singletons. In the present study (as in Moher & Egeth, 2012), there were no salient singletons; that is, all items were equally salient. It is possible that some form of rapid disengagement is operative in such circumstances. If rapid disengagement is not responsible, what other kind of mechanism might account for the observed change in performance? Some investigators have argued that active suppression can prevent the allocation of attention to known distractors (e.g., Sawaki, Geng, & Luck, 2012). Distinguishing the role of active suppression and rapid disengagement in the circumstances of the present experiments will require additional empirical efforts.

It seems that learning plays a major role in whether feature inhibition results in a cost or a benefit. The ability to hone selection mechanisms to efficiently choose information to attend and information to ignore is critical for understanding how observers strategically search within visual environments.

Author Contributions

Both authors contributed to the study design. Testing and data collection were performed by C. A. Cunningham. C. A. Cunningham analyzed and interpreted the data under the supervision of H. E. Egeth. C. A. Cunningham drafted the manuscript, and H.E. Egeth provided critical revisions. Both authors approved the final version of the manuscript for submission.

Declaration of Conflicting Interests

The authors declared that they had no conflicts of interest with respect to their authorship or the publication of this article.

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Note

1. We would like to thank John Jonides for pointing out this potential problem.

Chapter 3: Inhibition Drives Feature-based Attention

Chapter 3: Synopsis of Completed Experiments

When a target feature is in competition with a distractor feature, inhibition of the distractor, rather than activation of the target, is what biases early feature-based attention (Moher, Lakshmanan, Egeth, & Ewen, 2014). Critically, in previous studies only a single target feature was in competition with a single distractor feature. What happens when a target feature is in competition with multiple distractor features? In the completed experiments below, we demonstrate that even in the face of multiple distractor features, inhibition of distractors, rather than activation of the target, drives early feature-based attention. Additionally, we are interested in understanding whether it is a generalizable phenomon that inhibition drives early feature-based attention. Specifically, it still remains to be seen if target and distractor feature *consistency* is what facilitates inhibition driving feature-based attention. For example, in the previous work (Moher et al., 2014) and in the current findings below (i.e., two distractor work), both the target and distractor information remained consistent throughout the task. This allowed for the possibility that observers could learn to ignore the non-target information. Therefore, learning could be a key component in whether the attentional system utilizes inhibitory processes in early feature-based attention.

To test this, we used a similar paradigm as detailed in the completed experiments, but changed a couple critical components. The most critical change we made is that we made the target feature consistent throughout the task, but varied the to-be-ignored distractor feature from trial to trial. By changing the distractor feature from trial to trial, we create a situation where if the attentional system *can* use excitation of target features to drive early feature-based attention (which has yet to be seen in either Moher et al. (2014) or in the work detailed below), then by making the distractor information highly inconsistent, we should create the ideal situation for excitation of target features to occur. However, if we still find that the neural data from participants suggests that inhibition is driving early feature-based attention, then this would be a strong case for the generalizability of this phenomenon.

Title: Attention is driven by inhibition: Suppression of multiple distractor features facilitates target selection

Under Review at Visual Cognition

Abstract

Due to the limited information processing capacity of the human visual system, it is critical to selectively respond to those stimuli that are the most relevant to our current goals. Inhibition of non-target information has been shown to play a role when selecting target feature information, however the generality of that mechanism has yet to be explored. While past work has demonstrated that inhibition of distractor information can drive feature-based attention, those experiments utilized stimuli in which there was only a single target feature and a single non-target feature. This scenario is far removed from everyday life where a target may appear in a heterogeneous background in which more than one feature may be irrelevant. Here we investigated whether early feature-based attention is facilitated by suppression of distractor feature information when multiple (here, two) distractor features are present. Presenting multiple distractor features along with a single target feature may push the attentional system into a state where inhibiting two distractor features is more costly than activating a single target feature. Contrary to this expectation, we found that even when

observers are presented with multiple distractor features in the presences of a single target feature, inhibition of the distractor features is what drives feature-based attention. This work provides new evidence in support of current models of visual attention, which will need to reconsider the major role that inhibition plays in selection.

Introduction

The visual system is limited in its capacity for higher-order processing. Therefore, making appropriate responses to external stimuli depends on the selection of visual inputs that are relevant to our current goals. This kind of selection process (sometimes referred to as top-down attention), can occur on the basis of several stimulus attributes including location (Posner, 1980; Serences, Yantis, Culberson, & Awh, 2004; Shomstein & Gottlieb, 2016), color (Egeth et al., 1984; Saenz, Buraĉas, & Boynton, 2003), orientation (Liu, Larsson, & Carrasco, 2007), and direction of motion (Saenz et al., 2003). Using event-related potential (ERP) recordings, it has been shown that processing of task-relevant features throughout the visual field can be influenced by current goals as early as 100 ms following stimulus presentation (Zhang & Luck, 2009).

Attentional selection based on a property such as color is usually described in terms of the activation of task-relevant features (Wolfe, 1994a),

which may be accomplished by an increase in the gain of neurons tuned to features of the target (Martinez-Trujillo & Treue, 2004; Saenz, Buracas, & Boynton, 2002). However, recent research has shown that inhibition of non-target information can also play a role in target feature selection (Andersen & Müller, 2010; Braithwaite & Humphreys, 2003; Cunningham & Egeth, 2016; Lleras, Kawahara, Wan, & Ariga, 2008; Moher et al., 2014; Stormer & Alvarez, 2014; Woodman & Luck, 2007). There is evidence that features can be de-prioritized in several different paradigms including visual marking (Braithwaite & Humphreys, 2003) and the distractor preview effect (Lleras et al., 2008), However, while electrophysiological data indicate that location-based inhibition can occur during early stages of visual processing (about 100 ms post-following stimulus presentation (Luck & Hillyard, 1994a; Luck et al., 1994)), evidence of feature-based inhibition has typically been found only at later stages of processing (starting approximately 200-300 ms after stimulus presentation; (Andersen & Müller, 2010; Shin, Wan, Fabiani, Gratton, & Lleras, 2008; Stormer & Alvarez, 2014)).

The possible existence of early feature-based inhibition was demonstrated (Moher et al., 2014) by adapting a previously used (Zhang & Luck, 2009) ERP design. Observers viewed a continuous stream of two spatially interleaved sets of dots in one visual hemifield while maintaining central fixation.

Observers were instructed to indicate whenever the target-colored dots were simultaneously dimmed for 500 ms, but to ignore occasions when it was the distractor-colored dots that dimmed. During each trial, task-irrelevant homogeneously colored sets of dots (probes) were occasionally presented in the opposite hemifield. Within each trial, each set of probe dots was randomly selected to be composed of dots matching either the target color from the task-relevant side, the distractor color from the task-relevant side, or a neutral color that never appeared on the task-relevant side (the latter served as the baseline condition).

Changes in the amplitude of the P1 response to these probe stimuli were examined to clarify the effects of feature-based attention on early visual processing. The P1 is an ERP component that reflects an early sweep of visual processing (approximately 100 ms after stimulus presentation) whose amplitude can be affected by changes in neuronal activity in extrastriate cortex (Mangun, Buonocore, Girelli, & Jha, 1998; Woldorff et al., 1997) that may reflect top-down attentional control settings (Hillyard & Münte, 1984). The P1 is typically interpreted to reflect a feedforward wave of sensory processing (Hillyard, Vogel, & Luck, 1998; Luck & Kappenman, 2012; Zhang & Luck, 2009); but see Foxe and Simpson (2002), for an alternative interpretation.

Given that enhancement and inhibition are both plausibly related to attentional selection, one might expect to find evidence of both. However, keeping in mind that feature-based inhibition only occurred later in processing (around 300 ms post-stimulus) in previous studies (Andersen & Müller, 2010; Shin et al., 2008; Stormer & Alvarez, 2014), it is also plausible to think that no inhibition at all would be observed in the early P1 component. Interestingly, the effect that was observed in Moher et al. (2014) appears to consist of pure inhibition: the target and the neutral ERPs were essentially identical in P1 amplitude, while the distractor P1 was substantially reduced. A behavioral follow-up revealed that this was indeed due to inhibition of distractor features (Moher et al., 2014).

Thus, when one target feature (e.g., red) and one distractor feature (e.g., blue) are in competition in a display, inhibition of the distractor feature information, rather than the activation of the target feature, is what drives early feature-based attention. In the world outside the laboratory a critical target feature is typically visible in a scene with many competing nontarget features. Therefore, the neural and cognitive processes involved in more complex situations when there is one target, but more than one distractor feature remain unclear. In these situations, when the human visual system is faced with a

computationally more complex problem, will inhibition still drive feature-based attention in the face of multiple distractors?

Experiment 3

In the present study, we used electrophysiological recordings to directly test whether or not inhibition of distractor features drives selection in situations where there are multiple distractor stimuli. We presented observers with a visual monitoring task while recording neural activity with electroencephalography (EEG). Observers were instructed to fixate at the center of the screen while being presented with a continuous stream of three spatially interleaved sets of dots (one target color and two distractor colors) in one hemifield (see Figure 3.1). Every 100 msec, half of the dots would randomly relocate, giving the array of dots a scintillating, motion-like appearance. Randomly throughout the trial, the entire set of target-colored dots would undergo a brief luminance decrement (500 ms). Observers were instructed to respond when the target-colored dots dimmed. Additionally, each set of distractor-colored dots independently dimmed in the same way. Observers were instructed to not respond when distractor dots dimmed. In the opposite hemifield, probes were randomly presented throughout the trial. The probes could be the target color,

either of the distractor colors, or a neutral color (i.e., a fourth color, never present in the task-relevant hemifield). Critically, while the probes were irrelevant to the subject's task, they elicited a P1 response in the EEG. By measuring P1 amplitudes to unattended probes, we were able to assess whether there were differential effects of feature-based attention to these probes.

Methods

Participants

A group of 24 Johns Hopkins University undergraduate students and community members with normal or corrected-to-normal visual acuity and normal color vision participated in sessions lasting approximately 90 min. The participants received monetary payment as compensation and gave informed consent. The protocol was approved by the Johns Hopkins Medicine Institutional Review Board.

Equipment

EEG recording and EEG data analysis methods were largely adapted from (Moher et al., 2014). Stimulus presentation was conducted using MATLAB (Mathworks) and PsychToolbox (Brainard, 1997). Electroencephalogram (EEG) data were recorded at 47 sites covering the whole scalp with approximately uniform density using an elastic electrode cap— Waveguard cap (Advanced

Neuro Technology, or ANT, The Netherlands) with 128-channel Duke layout (equidistant electrode placement)—referenced to the average of all channels during recording. Electrode impedance was kept below 5 kΩ. All EEG channels were recorded continuously in direct-current mode at a sampling rate of 512 Hz from a 128-channel, high-impedance ANT Waveguard amplifier with active cable-shielding technology and an antialiasing low-pass filter with a 138 Hz cutoff.

Procedure and design

Prior to the onset of a trial, an arrow appeared which cued observers to the relevant "attended" side (the attended side was randomized by trial). At the beginning of the experiment, observers were told to attend to a specific target color and to respond any time that color (e.g., red) underwent a luminance change (i.e., dimmed). Observers responded by pressing the trigger on a gamepad. They were also instructed not to respond when the distractor dots (e.g., blue and green) underwent luminance changes. There were 4 colors used in the experiment: red, blue, green, and yellow. The roles of specific colors (i.e., as target, distractors, or neutral) were counterbalanced across participants. Each color appeared at a luminance of 8.1 cd/m^2. On the task-relevant side, the

luminance of all of the dots of one color was occasionally reduced to 3.2 cd/m^2. The fourth color was assigned to be a "neutral" color, and only appeared as a probe on the task-irrelevant side. During the 15 second trial, half of all dots on the attended side were randomly relocated every 100 ms within an imaginary circle, giving the dots a motion-like appearance. Throughout the trial, the set of target dots and the two sets of distractor dots would randomly, and independently, undergo brief (500 ms) luminance decrements before returning to their original luminance. During a given trial, these luminance changes occurred between 2 and 5 times each for the target colored dots and the distractor colored dots. Finally, on the "unattended" side, probe dots were presented for 100ms at interstimulus intervals (i.e., between luminance changes of the target dots and distractor dots) that varied randomly from 217 to 700 ms. Observers were instructed to ignore the unattended side and not respond to the probe dots. Observers completed 128 trials total.

EEG Data Analysis

Electroencephalogram (EEG) data were recorded at 47 sites and referenced to the average of all channels during recording. EEG epochs were synchronized with the onset of probe dot presentation and analyzed using Advanced Neuro

Technologies's (The Netherlands) asa-lab software. Vertical electrooculograms were recorded from frontal channels LL1 and RR1, whose locations were designed specifically to capture eye blinks. (See electrode diagram in (Moher et al., 2014)). Horizontal electrooculograms were recorded from channels LE1 and RE1. Eye blink correction was performed using a principal component analysis method (Ille, Berg, & Scherg, 2002). After eye blink correction, EEG was visually inspected on a trial-by-trial basis to look for any horizontal eye movements. Any trials contaminated with horizontal eye movements were eliminated from averaging. In addition, trials contaminated with excessive muscle artifacts, artifacts due to movements, or trials in which amplifier blocking occurred were also eliminated. An off-line bandpass filter (Butterworth filter, low cut-off frequency = 0.2 Hz, high cutoff frequency = 35 Hz, and linear roll-off = 24 dB/octave) was applied to all channels. ERPs were averaged off-line from 100 ms before to 600 ms after probe stimulus onset. Data were analyzed from six spatially contiguous electrodes in each hemisphere (LA5, LB4, LC6, LE3, LL10, LL13; RA5, RB4, RC6, RE3, RR10, and RR13), similar to (Moher et al., 2014). Within each subject, electrodes were included in the individual's average based on the presence of a discernible P1 pattern. These channels were selected in a blind fashion, where the true experimental conditions were not considered (no labels were present for these waveforms during selection). Finally, ERP

waveforms obtained from the selected electrodes were grand averaged using EEGLAB, a MATLAB toolbox (Delorme & Makeig, 2004) and ERPLAB (Lopez-Calderon & Luck, 2014). Mean P1 amplitude (Moher et al., 2014) was calculated for each participant as the mean amplitude from the point in time when the voltage reached 50% of peak amplitude to 50 ms after that point. Peak P1 amplitude was calculated as the highest amplitude within the time window of 90ms to 140ms.

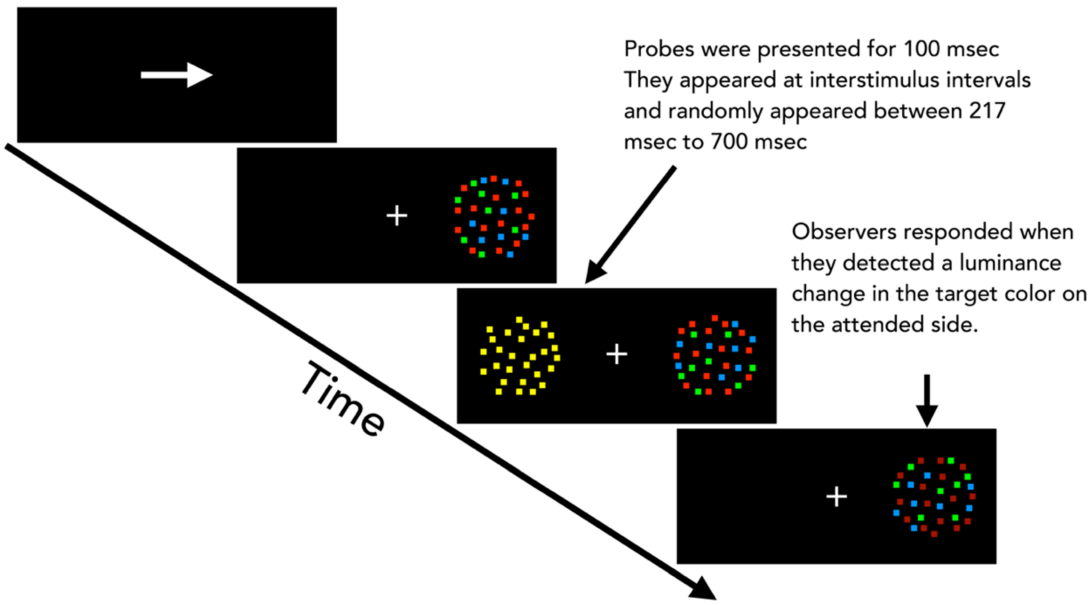

Figure 3.1 A sample of frames within a trial. Observers were told to attend to a specific target color (e.g., red) for the entire session and to respond any time the attended color underwent a luminance change (i.e., dimmed). Note that the current figure is not to scale and differs from the actual displays in terms of the total number of dots in each "cloud."

Results and discussion

Behavioral results revealed that the average accuracy for the detection of target luminance changes in Experiment 3 was 78%, with a false alarm rate of 8%. Critically, P1 amplitudes associated with the presentation of probe displays differed as a function of the type of probe display (e.g., target color, distractor colors, or neutral color). ERP results revealed a main effect of probe type on

peak P1 amplitude, $F(2, 46) = 5.601$, $p = .011$, Greenhouse-Geisser corrected. There was no effect of hemifield or interaction between hemifield and probe type (*ps* > .5). We found the same results when measuring mean P1 amplitudes, rather than peak amplitude, $F(2, 46) = 10.096$, $p = .001$, Greenhouse-Geisser corrected. Pairwise comparisons revealed that the P1 amplitudes associated with the presentation of target and neutral colored probes did not differ from one another, $p > 0.05$. However, P1 amplitudes associated with distractor probes were significantly different from target and neutral probes, *ps* < 0.05. These results suggest that neural activity associated with target probes was no different than neutral probes, which were never presented on the attended side of the behavioral task. Rather, P1 amplitudes to distractor probes, as seen in Figure 3.2, were significantly reduced compared to target and neutral probes. These results suggest that in more complex environments where activating a single target feature might seem more advantageous, the human visual system attempts to inhibit multiple distractor features to facilitate the selection of a target feature.

Our results suggest that on average participants were able to suppress both of the distractor colored probes, which resulted in the lower average distractor P1 compared to the target and neutral colored probes. It is an interesting question

to consider whether this mean difference indicates that subjects can suppress both distractor colors simultaneously, or whether the mean difference indicates suppression of just one, while the other undergoes little or no suppression. Unfortunately, the design of the present experiment does not lend itself to an analysis that can address whether there are indeed differential amounts of suppression for individual distractors, rather we can only address whether there was suppression for the average of the two distractors.

There are some superficially appealing post hoc analyses that might be considered. For example, we can try to explore the magnitude of the difference between the P1 values for the two distractors colors assigned to each subject. If the difference is very small, this would support the idea that subjects can suppress both distractors simultaneously. And indeed, inspection of individual ERP plots suggests that some subjects show just such a pattern, whereas others do not. However, trying to analyze the results quantitatively is not really possible given the design of the experiment. For example, suppose we take for each subject the difference between the higher and lower of the P1 values associated with the two distractors assigned to him or her, and see if that difference is significantly different from zero. But if we consistently subtract lesser from greater each difference score will be positive and thus the mean effect will be

meaninglessly significant. If we randomly assign one distractor to the category "Distractor 1" and the other to "Distractor 2" then the difference between category means will tend toward zero. In future work, we will be exploring the extent to which the suppression we have found is attributable roughly equal suppression of the two distractors as opposed to being driven by suppression of just one of the distractors.

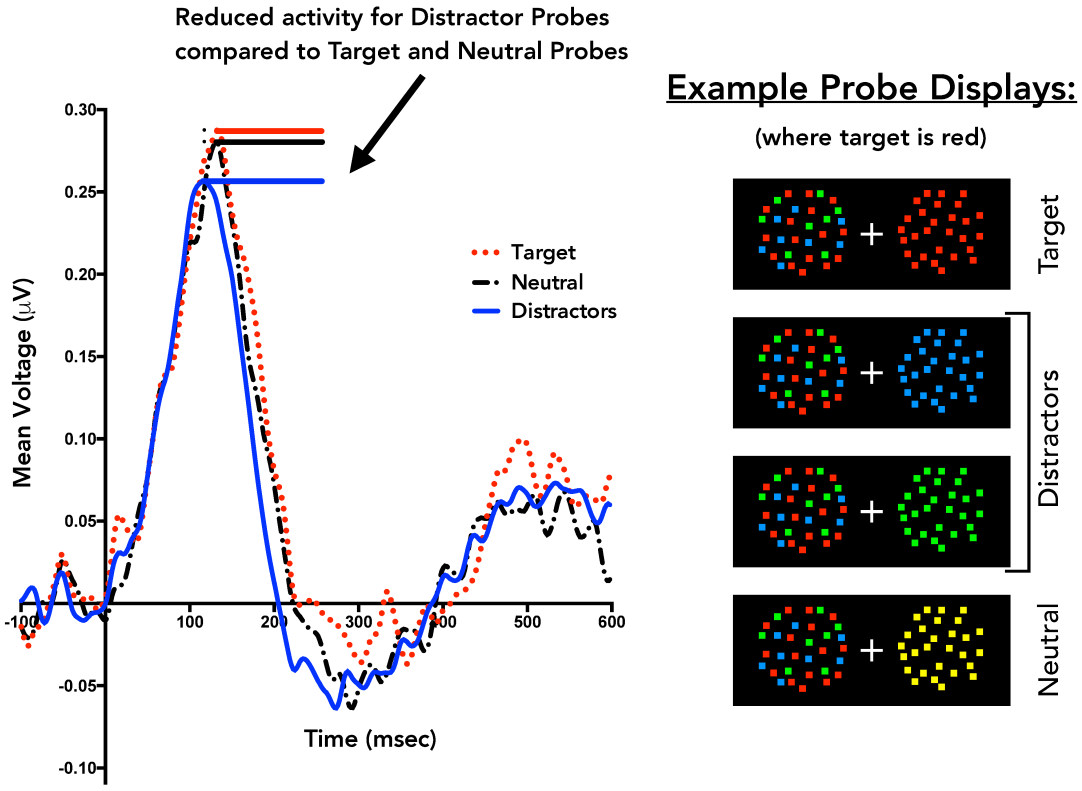

Figure 3.2 ERP results from Experiment 3. Mean Grand average waveforms, time-locked to the presentation of the probe dots (collapsed across hemispheres) contralateral to the visual hemifield where task-irrelevant probes were presented. Stimulus onset (i.e., probe dots) occurred at 0 ms.

Experiment 4

Previous research has shown that learned attentional sets can have long-lasting biases, even when the task demands change (Graves & Egeth, 2016; Leber & Egeth, 2006; Leber, Kawahara, & Gabari, 2009; Moher et al., 2014; Zehetleitner, Goschy, & Müller, 2012). Much of this previous research relied on experimental setups that involved a "transfer task" after a period of training or experience with a "training task". Specifically, the goal of the transfer task is to probe any lingering attentional biases to previously learned information, even though that information is totally irrelevant in the new task (and generally is randomly presented/manipulated). Interestingly, there should be no differences in responses to different elements in the transfer task if no learning occurred in the training task. In contrast, if there do appear to be differences in the transfer task, they can therefore be attributed to the prior learning from the training task (e.g., Moher et al. 2014). In Experiment 4 we sought to obtain converging behavioral evidence for the inhibitory effect found in Experiment 3 by using a two-phase transfer design. In the first phase we presented participants with the same task from Experiment 3, henceforth referred to as the "training task," and in the second phase presented them with a transfer task (see Figure 3.3A). In the

transfer task, observers were presented with two random shapes displayed on the left and right side of a fixation cross. One of the shapes contained a tilted line and one contained a vertical line. Observers were asked to report the orientation of the tilted line (i.e., left or right) using the arrow keys. They were told that the color and shape were irrelevant and to remain fixated for each trial. Every color and target/distractor combination occurred (e.g. red could be the color of the target (tilted line) on one trial and be the color of the foil (vertical line) on another trial).

Methods

Participants

A new group of 32 Johns Hopkins University undergraduate students and community members with normal or corrected-to-normal visual acuity and normal color vision participated in experimental sessions. The participants received extra credit in undergraduate courses and gave informed consent. The Johns Hopkins Homewood Institutional Review Board approved the protocol.

Procedure and design

All participants were given a training and a transfer task. The training task was the same as the task in Experiment 3 with the exception that subjects were not outfitted for EEG. In the transfer task five colors were used: the four from

Experiment 3 (red, blue, green, yellow) and purple. The roles of the original four colors were counterbalanced across subjects as in Experiment 3. In addition, purple was used as a novel color and appeared only in the transfer task. The transfer task displays(see Figure 3.3a) consisted of two different geometric shapes presented one on each side of fixation. The experiment contained 4 geometric line shapes that were enclosed in a square. For each trial, two different shapes were randomly chosen such that the same shape never appeared on both sides. One of the shapes contained a tilted line and one contained a vertical line. The assignment to shape and side were random on each trial. Across all trials every color and target/distractor combination occurred in a fully randomized fashion (e.g. red could be the color of the target (tilted line) on one trial and be the color of the foil (vertical line) on another trial). Stimulus displays were presented until response. The shapes subtended a visual angle of approximately 5.2° by 5.2°. They were presented 6.5° from the center of the fixation cross. Between the stimulus displays of successive trials, a black screen with a fixation cross appeared in the center for 1000 msecs. Reaction times and error rates were measured. There were 300 trials.

Results and discussion

Overall, the statistical analyses indicated that there were no statistical

differences in the second half of the 300-trial transfer task, which is similar to previous findings (Moher et al., 2014). However, there was strong evidence of immediate transfer in the first half of the transfer task. The logic of the experiment can best be appreciated with reference to Figure 3.3. Consider, as an example. the case where in the training phase the target was red, the distractors were blue and green, the neutral color was yellow and a novel color, not used in the training phase, was purple (Figure 3.3B). Assuming transfer of training, if it were the case that observers were activating the (previous) target color (here red), rather than inhibiting distractor colors, then there should be no difference in performance regardless of whether the foil line in the transfer task is the previously used distractor color, previously used neutral color, or novel color, since observers would simply activate the target color in all of those instances. Alternatively, if observers had suppressed distractor features rather than activated target features in the training task, then reaction times should be faster in the transfer task when the foil line is in a color that was previously used as a distractor (here green) in the training task, compared to when the previously neutral (yellow) or novel color (purple) contains the foil line. Speaking colloquially, green (or blue) foil lines should be easy to ignore. The mean RTs shown in Figure 3.3b show just this latter pattern of results. For Figure 3.3b, there was a significant interaction of Block (i.e., first half vs. second half of the

experiment) and the color of the foil shape (i.e., previous Distractor color, previous Neutral color, or Novel color) $F(2, 62)=6.615$, $p=.003$, Greenhouse-Geisser corrected. Specifically, we found that when the previous Distractor Color (i.e., the green/blue bar in Figure 3.3b) contained the foil item, those trials were significantly faster than when either the previous Neutral color or the Novel color contained the foil item ($ps < 0.05$, Bonferroni corrected for multiple comparisons). Additionally, as mentioned above, the second half of the transfer task had no significant differences ($ps > 0.05$).

Additionally, as shown in Figure 3.3C, we find corroborating evidence that observers are not activating target features. We examined RTs for trials in which the target line was in one of the previous distractor colors (here green). We compared reaction times for when the item containing the foil line was either the previous target color (red), the previous neutral color (e.g., yellow), or the novel color (e.g., purple). If it were the case that observers were prioritizing target features, then trials where the target color was present (red bar in Figure 3.3C) should yield slower RTs (i.e., participants would be initially attracted to the red distractor, which was previously the target, and have to disengage from it) compared to trials with the previous neutral color (yellow bar Figure 3.3C) or the novel color (purple bar Figure 3.3c). We found no significant differences when

comparing any of these trial types (ps > 0.05), suggesting that prior service as a target feature during the training session neither helped nor hindered performance in the transfer task.

We also examined whether search for a target tilted line in either the (1) previous Neutral color or (2) the Novel color would differ depending on what colors were assigned to the foil line (i.e., previous Distractor colors, previous Target color, Novel color or previous Neutral color respectively). While for the comparisons involving the target line colored in the Novel color there was a significant effect of Block ($p < 0.05$) indicating a linear trend toward faster responses generally in the second half of the experiment, there were no other significant differences.

Taken together, these data and the data from Experiment 3 provide some converging evidence that the feature-based attentional set learned from the training task was defined by inhibition of the multiple distractor features (on average). Importantly, the findings from Experiment 4 indicate that this inhibitory effect might also be context dependent. Consider first the results depicted in Figure 3.3B. The significant effect shown there might indicate that blue and green distractors were inhibited in general. However, if this were the

case we might expect a similar speeding of reaction time if the tilted line target was presented in a neutral color (here, yellow), and the foil (vertical) non-target was presented in blue or green. But the analysis presented in the preceding paragraph indicates that this was not the case. That is, it appears that during the training phase subjects learned to suppress green and blue dots only in the context of red dots, suggesting a learned response to a kind of specific mapping (Shiffrin & Schneider, 1977).

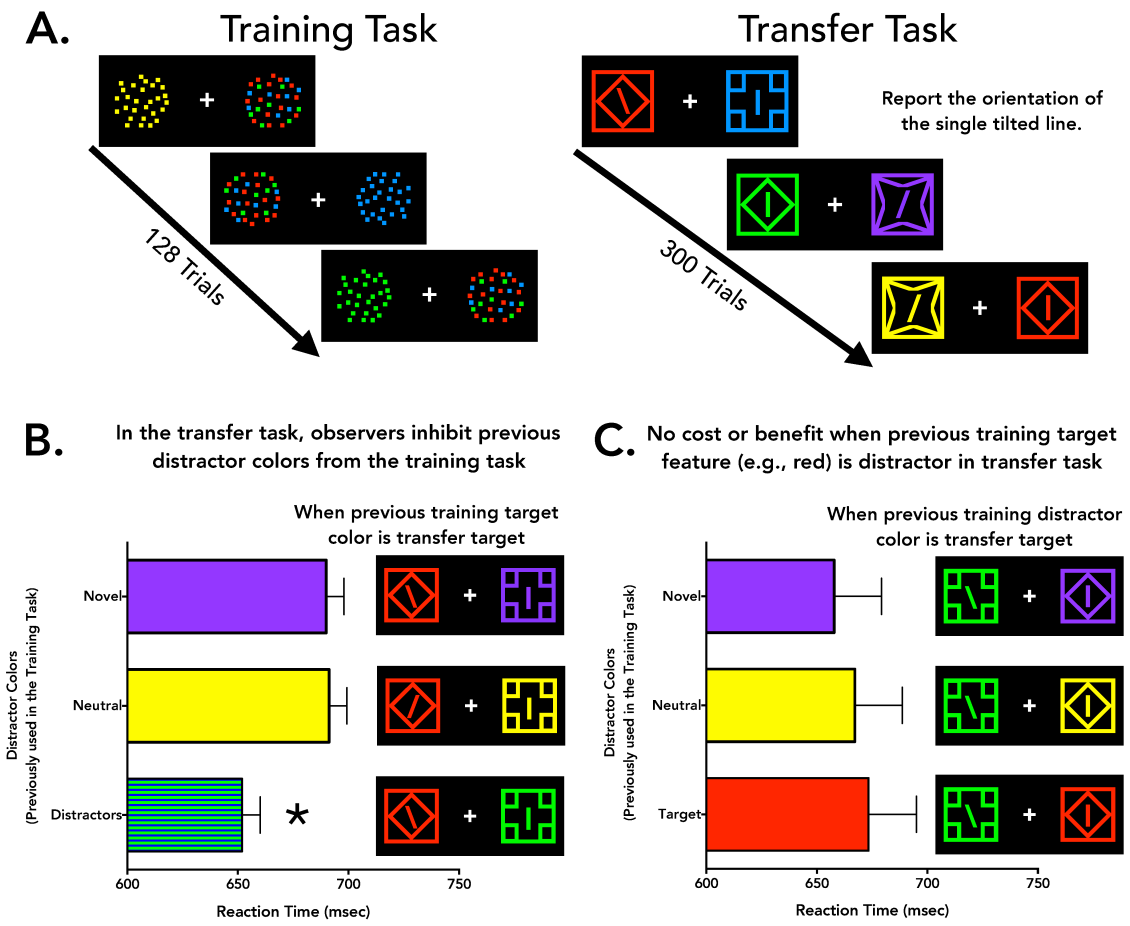

Figure 3.3 Design and results from Experiment 4. (A) A sample of trials from the training and transfer tasks used in Experiment 4. (B) Average reaction times (for the first half of the transfer task) for trials where the previous target color from the training task (in this example, red) contained the target tilted line. Reaction times were fastest in this trial type when the same colors that were previously used as distractors in the training task (in this example, blue and green) contain the foil line in the transfer task, compared to when the previously used neutral (in this example, yellow) or novel color (in this example, purple) contain the foil line. (C) Average reaction times (for the first half of the transfer task) for trials where the previous distractor color from the training task contained the target tilted line. There was no significant difference ($p > 0.05$) in reaction times when the distractor in the transfer task (i.e., the shape that contained the foil line) was either the previous target color, neutral color, or a novel color. Error bars show ±1 SEM calculated within-participants (Cousineau & O'Brien, 2014).

General Discussion

The current study demonstrates that feature-based attention is driven by

inhibition, even in the face of multiple distractors. While previous research has suggested that inhibition could have a role in early feature-based attention (Andersen & Müller, 2010; Moher et al., 2014; Zhang & Luck, 2009), observers in those studies were only presented with situations with one target feature and one distractor feature. It could be the case that when there are multiple distractors present, excitation of the target feature takes over. However, the current results suggest something quite different. Specifically, it seems that even when the distractor-target feature relationship is unequal (2 distractors vs. 1 target), processes involved in early feature-based attention, on average, still rely on inhibition. These results support an attentional framework in which feature-based attention could be *mainly* driven by inhibition of competing information.

It is not clear why, in some circumstances, the attentional system inhibits distractor features rather than activating a single target feature. One reason this could be the case is that inhibition, compared to excitation, has been suggested to be more metabolically efficient (Buzsaki, Kaila, & Raichle, 2007; Waldvogel et al., 2000). Another possibility is that computations similar to those involved in center-surround suppression in the spatial domain may be used in non-spatial feature spaces such as color (Chen & Tsotsos, 2010). A center-surround architecture amounts to attending to a restricted region in a multidimensional

space. If a center-surround architecture is in play, a multidimensional volume of other colors surrounding that restricted central area will be inhibited, thus directly accounting for the ability to inhibit multiple distractor colors as demonstrated in the present experiment. Center-surround mechanisms typically have a delimited region of suppression. Stimuli close in either real (Anton-Erxleben, Stephan, & Treue, 2009; Hopf et al., 2006; Mounts, 2000; Muller & Kleinschmidt, 2004), perceptual (Chen & Tsotsos, 2010), or conceptual (Carr & Dagenbach, 1990; Dagenbach & Kubat-Silman, 2003; Stone & Valentine, 2007) space to the target are inhibited more than stimuli further from the target. There is some evidence of just such a non-monotonic effect of perceptual similarity in the color domain in a study that measured steady-state visual evoked potentials (SSVEPs; (Stormer & Alvarez, 2014)). However, it is not clear whether the critical distances obtained in that study are applicable in the present paradigm. Note that the center-surround-like results imply that both inhibition and excitation were observed in that study. These results are not incompatible with the present study or (Moher et al., 2014), as SSVEPs might reflect both early and late processes (i.e., activity was averaged from 400 ms to 2,500ms after stimulus onset). More detailed investigation is called for.

Linear separability of target color information from distractor color information is

an interesting consideration for future work. Specifically, it has been shown that visual search can be influenced by the relationship in color space of a target color to distractor colors (Bauer, Jolicoeur, & Cowan, 1996; Bauer, Jolicoeur, & Cowan, 1998; Stroud, Menneer, Cave, & Donnelly, 2012). Additionally, recent work by Won & Geng (in review) suggests that while observers can inhibit multiple specific distractor features, this kind of inhibition also has some board tuning that allows for other similar features to be easily inhibited. In the present task, colors were chosen subjectively to represent clearly perceptually distinct color categories. All four of the colors used in the dots task of Experiment 3 were linearly separable from one another (i.e., all four were on a convex hull). Such a set of colors may have increased the likelihood that we were able to show that on average the two distractors could be inhibited. Further research should explore whether this outcome is limited to the case of linear separability. Previous work also suggests that it would be fruitful to explore more generally the roles of target-distractor similarity and distractor-distractor similarity in multi-feature inhibition (Duncan & Humphreys, 1989)

Our findings have implications for understanding the nature of visual attention, as well as professional search (e.g., radiology and airport baggage screening). Specifically, when there is high competition between multiple signals, it seems

that inhibition of multiple sources of distractor information, rather than excitation of target information, is a major driver of feature-based attention. Current models of visual attention will need to consider the critical role that inhibition plays in selection. For example, the Guided Search model (Wolfe, 1994a; Wolfe et al., 1989) suggests that top-down "commands" are applied to lower level feature maps to activate locations that contain relevant attributes. Wolfe describes a parallel process that assigns weights to features related to targets and distractors. Our findings could provide neural evidence of this parallel stage of processing and demonstrate that it could be the case that inhibition, rather than excitation, is how these weights are applied. Specifically, it seems that to disentangle target features from distractor features, inhibitory weights are applied to those features associated with distractors. These inhibitory weights by their very nature create dissimilarity between target-related features and distractor-related features, leaving targets with higher activation. This information is then sent on to an "Activation Map" where feature weights are integrated into topographic maps where attention is attracted to areas with the most activation. However, it is also important to note that while these findings might contribute to our knowledge about current attentional models, many of the models are built on findings from experiments that involve traditional visual search paradigms rather than sustained attention tasks like in the current study

and in Zhang and Luck (2009) and Moher et al. (2014). Therefore, it could be the case that the nature of attention to target information in a visual search task (where there is generally distractor uncertainty) is quite different compared to attention to target information in a sustained attention task (where there is considerable certainty in the distractor information). Finally, these results could also be informative, in a similar way, to the dimension-weighing account (Found & Muller, 1996), as it relies on many of the same assumptions as Guided Search (Wolfe, 1994a).

Acknowledgments

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Chapter 3: Follow-up Experiment 5

In the work described above, we examined whether inhibition still drives early-feature-based attention in situations that are somewhat more similar to the real world. Specifically, we tested how the attentional system responds when observers are given a situation where they need to attend to a single target feature, but inhibit multiple (i.e., two) distractor features. Our results suggest that the attentional system still depends on the inhibition of multiple distractor features to be able to attend to target feature information. However, it remains to be seen if inhibition in early-feature-based attention is what drives target selection in all situations. For example, in the previous work (Moher et al., 2014) and in the current findings above, both the target and distractor information remained consistent throughout the task. This allowed for the possibility that observers could learn to ignore the non-target information. Therefore, learning could be a key component in whether the attentional system utilizes inhibitory processes in early feature-based attention. To test this, I utilized our two simultaneous distractor (TSD) paradigm detailed above but changed some of the critical components. First, in this version the setup was similar to Moher et al. (2014), where we had two colors presented in each display: one target and one distractor. Second, we made it so that each participant was assigned one consistent target feature throughout the task, but the distractor feature changed

from trial to trial (e.g., the subject would attend to red, but on trial one the distractor color is blue and on trial two the distractor color is green). Thus, this paradigm will be referred to as the *multiple varying distractor* (MVD) paradigm. Finally, we added several colors to the experiment (7 total), so that there were plenty of distractor features to randomly choose from; this reduces the ability to learn a "set" of distractor features to ignore. By inconsistently changing the distractor feature from trial to trial, we attempt to create a situation where, if the attentional system *can* use excitation to target features to drive early feature-based attention (which has yet to be seen in either Moher et al. (2014) or in the TSD paradigm detailed above), then we should be able to detect it. However, if we still find that the neural data from participants suggests that inhibition is driving early feature-based attention, then this should be a strong case for the generalizability of this phenomenon.

Methods

Participants

A group of 42 Johns Hopkins University undergraduate students with normal or corrected-to-normal visual acuity and normal color vision participated in sessions lasting approximately 90 min. In previous work, 21-24 subjects have typically been used for these studies (e.g., Moher et al., 2014). However, due to the

number of colors we wanted to use and to correctly balance all conditions, we needed a minimum of 42 subjects. The participants received course credit as compensation. Research was performed in accordance with the Johns Hopkins Homewood Institutional Review Board. Informed consent was obtained from all participants in all experiments.

Design and Procedure

A sustained attention task (similar to Experiment 3 above) was administered to participants while EEG was recorded. Prior to the onset of a trial, an arrow appeared which cued observers to the relevant "attended" side (the attended side was randomized by trial). At the beginning of the experiment, observers were told to attend to a specific target color and to respond any time that color (e.g., red) underwent a luminance change (i.e., dimmed). Observers responded by pressing the trigger on a gamepad. They were also instructed not to respond when the distractor dots (e.g., either blue, green, aqua, purple, or orange) underwent luminance changes. There were 7 colors used in the experiment: red, blue, green, aqua, purple, orange, and yellow. The seventh color was assigned to be a "neutral" color, and only appeared as a probe on the task-irrelevant side. The roles of specific colors (i.e., as target, one of five distractors, or neutral) were counterbalanced across participants. All colors were isoluminant. During

the 15 second trial, half of all dots on the attended side were randomly relocated every 100 ms within an imaginary circle, giving the dots a motion-like appearance. Throughout the trial, the set of target dots and the set of distractor dots would randomly, and independently, undergo brief (500 ms) luminance decrements before returning to their original luminance. (Recall, that there is just one distractor color on each trial.) During a given trial, these luminance changes occurred between 2 and 5 times each for the target colored dots and the distractor colored dots. Finally, on the "unattended" side, probe dots were presented for 100ms at interstimulus intervals (i.e., between luminance changes of the target dots and distractor dots) that varied randomly from 217 to 700 ms. Observers were instructed to ignore the unattended side and not respond to the probe dots. Each cloud of probe dots was homogenous in color. Probe dot clouds could appeared in any of the seven possible colors in randomized order. Observers completed 125 trials total.

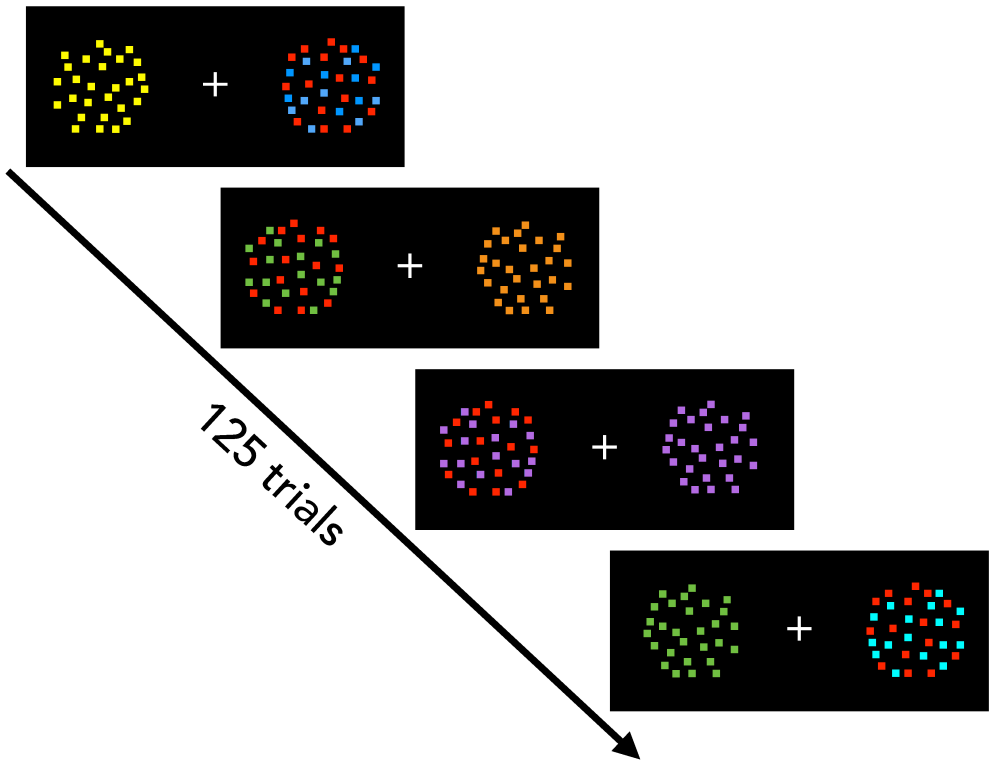

Figure 3.4 Examples of trials and stimuli from the Multiple Distractor Follow-up Experiment. Observers were first cued to the attended side (i.e., the side with two sets of different colored dots) with an arrow cue. They were told to attend to a specific target color (e.g., red) for the entire session and to respond any time the attended color underwent a luminance change (i.e., dimmed). Critically, the distractor dots would appear in any of five possible colors (randomly assigned per participant, here blue green, purple, orange, aqua). On any given trial, the distractor dots could be any of the 5 possible colors. The neutral color (e.g., here yellow) never showed up on the attended side. Similar to previous work (above and Moher et al., 2014) probes were presented for 100 msecs. They randomly appeared between 217 msec to 700 msec at interstimulus intervals. The order of the colored probes was presented randomly. There were also periods of time where no probe was presented. Note that the current figure is not to scale and differs from the actual displays in terms of the total number of dots in each "cloud."

EEG Analysis

EEG was recorded simultaneously from 32 Ag/AgCL electrodes mounted in an elastic cap and amplified by an ActiCHamp amplifier (BrainVision). The

experimental sessions were performed in a dimly lit, sound-attenuated, and electrically shielded experimental booth. Stimuli were shown using an Epson PowerLite Home Cinema 3000 projector. Stimuli were back projected through a hole outside the room onto a 76 cm x 76 cm projector screen inside the room. The pixel screen resolution was set to 1024 x 768, which resulted in a projected screen size of approximately 36 cm by 27 cm. Stimulus presentation, timing, and response recording were controlled by a Dell PC running under Windows, using Psychtoolbox (Brainard, 1997) for Matlab (Mathworks, Inc). The screen was set at an approximate viewing distance of 70 cm from the seated participant.

EEG data were sampled at 500 Hz. Data were online referenced to Cz and later were offline referenced to the average of all channels. Eye movements were measured through the two frontal eye channels (FP1 and FP2). All offline EEG and ERP data analyses were conducted through EEGLAB (Delorme & Makeig, 2004) and ERPLAB (Lopez-Calderon & Luck, 2014) toolboxes for Matlab. Timing of the stimulus presentation and event codes were corrected using a photodiode. Continuous EEG data were first filtered offline with a band pass of 0.01–80 Hz. Trials with eye movements, eye blinks, or excessive muscle movements were excluded from the analysis. Epochs began 100 milliseconds before the probe stimulus presentation and ended 600 milliseconds after the

beginning of the presentation. Artifact free ERPs were time-locked to the presentation of the probe stimulus display.

Data were analyzed from four spatially contiguous electrodes in each hemisphere (P3, P4, P7, and P8), which overlapped with the channels used on a different EEG system and montage in previous work (Moher et al., 2014). All analyses were performed on an average of the contralateral activity to probes in all 4 channels. We examined two attentional ERP components: the P100 and the P200. We also examined an additional sustained positive component from 300-600 milliseconds. This late sustained positive component overlaps with many other memory-like components. For example, it overlaps in electrode placement and time signature with the contralateral delay activity (CDA) (Vogel, McCollough, & Machizawa, 2005), the sustained posterior contralateral negativity (SPCN) (Fahrenfort, Grubert, Olivers, & Eimer, 2017), the late positive component (LPC) (Curran & Cleary, 2003), along with the more the recent positive contralateral delay activity CDAp (Feldmann-Wüstefeld & Vogel, 2018). In lieu of creating an additional naming scheme for this ERP component, we will refer to this component by its descriptive nature as the late sustained contralateral positivity. Due to the nature of the probe stimuli in this task, we only analyzed neural responses that were contralateral to the probe displays

(similar to the work above and previous work by Moher et al., 2014). This is because the ipsilateral side would pick up a mix of complicated signal from the attended/relevant side. Therefore, the cleanest signal for our design is to only consider neural responses contralateral to the probe display. To measure the P100 for each condition, we took a mean amplitude over the 40-150 milliseconds time window after the probe was presented. For the P200 we examined from 200-240 millisecond and for the late sustained contralateral positivity we examined from 300-600 milliseconds. We included the late sustained contralateral positivity in the analysis because we were interested in whether the dynamic nature of the changing distractor stimuli would result in sustained activity after each probe. The presence of such activity, particularly differential activity for proposedly "inhibited" distractors, would suggest that observers create an inhibitory attentional set a given trial period (since trials were long, ~15 seconds). Finally, we also included the P200 in the analysis, since it has been previously suggested to reflect selection through distractor feature suppression (Philips & Takeda, 2009).

Behavioral Results

Behavioral results revealed that the average accuracy for the detection of target luminance changes was 70% and the false alarm rate (i.e., incorrect responses to

distractor colored dots dimming) was 12%. This resulted in a d prime (d') of 1.81. In addition to measuring overall d' performance, we also found an interesting effect of repeated *distractor* colored probes, in the uncued field, on task performance. We examined whether having been recently exposed to either 1, 2, or 3 repetitions of different distractor colored probes on the unattended side (i.e., any of the five possible distractor colors assigned to a given participant), prior to making a response, would influence behavioral performance. To be clear, the brief dimming of the cloud distractor dots on the attended side may be preceded by numerous events. For example, these events might include: the dimming of the cloud of target dots, the presentation of a probe dot cloud in a distractor color on the unattended side, or the presentation of a probe cloud in either the neutral or target color on the unattended side. We looked at the three events preceding the dimming of the distractor dots on the attended side and found that overall performance (i.e., d primes) increased as a function of the number of distractor probes that were presented in the preceding three events prior to a response. Specifically, we demonstrate that if an observer was presented with **three** distractor probes prior to any given response (i.e., a target dimming, which would result in a button press or a distractor dimming, which would result in withholding a response unless they false alarmed) they performed significantly better compared to when only **one** distractor probe or

two distractor probes were presented. To evaluate this, we performed a repeated measures ANOVA on the number of distractor probes presented prior to a response. We found a significant effect on behavioral performance of the number of probes presented prior to a response, $F(2, 82) = 20.43$, $p < 0.001$, partial eta = 0.333. A significant linear effect was found, where performance (i.e., d') increased as a function of the number of distractor probes that were presented ($p < 0$ .001). Paired t-tests revealed all three probe conditions were significantly different from one another (*ps* < 0.05), with performance increasing as a function of the number of distractor probes that were presented (1 distractor probe d'=1.72, 2 distractor probes d'=1.82, 3 distractor probes d'=2.07).

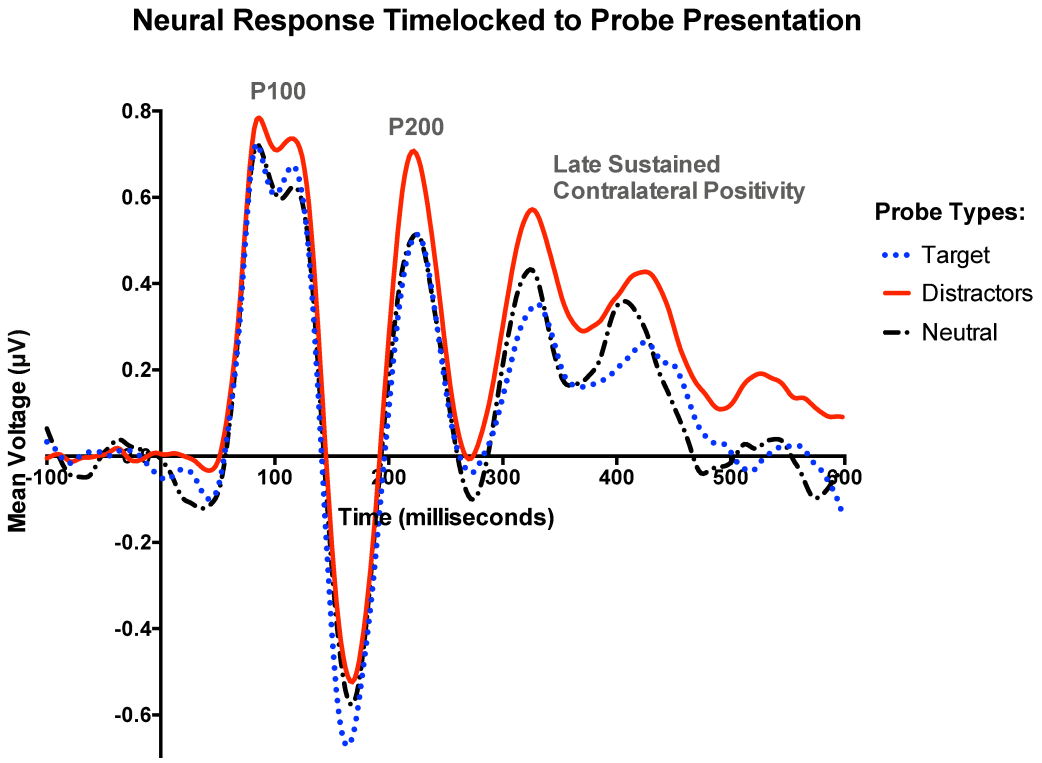

Figure 3.5 Results from Multiple Distractor Follow-up Experiment. Mean Grand average waveforms, time-locked to the presentation of the probe dots (collapsed across hemispheres) contralateral to the visual hemifield where task-irrelevant probes were presented. Stimulus onset (i.e., probe dots) occurred at 0 ms. A lowpass filter (35 Hz) was applied for graphing purposes only. However, all statistics were run with the original bandpass of 0.01–80 Hz and split by hemifield.

ERP Results

P100

Critically, P100 amplitudes associated with the presentation of probe displays differed as a function of the type of probe display (e.g., target color, distractor colors, or neutral color). ERP results revealed a *trending* main effect of probe type on mean P100 amplitudes, $F(2, 82) = 2.94$, $p = .06$, $\eta_P^2 = 0.07$ Greenhouse-

Geisser corrected. There was a significant main effect of hemifield, $F(1,41)=10.14$, $p = 0.003$, $\eta_P^2 = 0.2$ but no interaction between hemifield and probe type ($p = 0.85$). Pairwise comparisons revealed that the mean P100 amplitudes associated with the presentation of target and neutral colored probes did not differ from one another, $p = 0.71$. However, mean P100 amplitudes associated with distractor probes were significantly different from target ($p = 0.035$) and neutral probes ($p = 0.047$).

P200

We also analyzed P200 neural responses to probes. P200 amplitudes associated with the presentation of probe displays differed as a function of the type of probe display (e.g., target color, distractor colors, or neutral color). ERP results revealed a main effect of probe type on mean P200 amplitudes, $F(2, 82) = 3.50$, $p = .046$, $\eta_P^2 = 0.08$, Greenhouse-Geisser corrected. There was a no significant main effect of hemifield and no interaction between hemifield and probe type ($ps > 0.11$). Pairwise comparisons revealed that the mean P200 amplitudes associated with the presentation of target and neutral colored probes did not differ from one another, $p = 0.84$. However, mean P200 amplitudes associated with distractor probes were significantly different from target ($p = 0.043$) and neutral probes ($p = 0.004$).

Late Sustained Contralateral Positivity

Finally, we analyzed the Late Sustained Contralateral Positivity in neural responses to probes. The Late Sustained Contralateral Positivity amplitudes associated with the presentation of probe displays again differed as a function of the type of probe display (e.g., target color, distractor colors, or neutral color). ERP results revealed a main effect of probe type on mean Late Sustained Contralateral Positivity amplitudes, $F(2, 82) = 5.27$, $p = .012$, $\eta_P^2 = 0.11$, Greenhouse-Geisser corrected. There was a no significant main effect of hemifield and no interaction between hemifield and probe type (*ps* > 0.54). Pairwise comparisons revealed that the mean Late Sustained Contralateral Positivity amplitudes associated with the presentation of target and neutral colored probes did not differ from one another, $p = 0.58$. However, mean Late Sustained Contralateral Positivity amplitudes associated with distractor probes were significantly different from target ($p = 0.01$) and neutral probes ($p = 0.001$).

Discussion

We set out to better understand the role that distractor inhibition plays in early feature-based attention. Moher et al. (2014) found that distractor feature information, not target feature information, drives early feature-based attention.

However, in their experiments they had a single consistent target feature and a single consistent distractor feature. Therefore, it may be the case that when these types of features are held constant, the inhibition of distractor features is utilized over enhancement of target features. Our goal for this study was to create a situation that would *bias* the utility of early target feature information, in hopes of creating a situation where target feature enhancement would be most likely. To do this, we created a situation where target feature information was consistent by having participants only attend to a single target color throughout the whole experiment. In contrast, distractor feature information in our experiment was inconsistent due to the fact that we had five possible distractor colors. We increased the inconsistency of this information by randomly varying the to-be-ignored distractor feature from trial-to-trial. Therefore, if it is the case that target feature enhancement *can* drive early feature information, we have given it every opportunity to do so.

Across three ERP components related to attention and memory, we found differences in neural activity related to the presentation of uncued/unattended probe dot clouds. Surprisingly, we found that even though the target color feature remained constant throughout a given participant's experience, probes in this color were treated the same, neurally, as probes that never even

appeared in the actively attended task. Additionally, not only did we find that the target features were not enhanced beyond that of a neutral feature that was never part of the to-be-attended task, but also to our surprise we found that the dynamic changing distractor features, on average, resulted in very different neural signatures compared to the target and neutral features. Specifically, we found that there was increased P100 and P200 activity for distractor colored probes, compared to neutral probes and target probes, which didn't different from one another. Additionally, we found a differential Late Sustained Contralateral Positivity to distractor colored probes compared to both target probes and neutral probes. These results taken together suggest that differential cognitive processes are occurring for distractor features compared to target features. Moreover, since neutral colored probes were never part of the actual attended task, it seems that target feature probes are not treated any different than a color that was never directly interacted with. Taken together, and borrowing the logic from Moher et al. (2014), it seems that distractor features are critical in facilitating early feature-based attention.

Previous work on the P100 (Moher et al., 2014; Zhang and Luck, 2009) has demonstrated that it is sensitive to early feature-based attention. Additionally, other work has demonstrated the P200 component is related to early sensory

gating that discards irrelevant information to aid attentional processing (Lijffijt et al., 2009). While both of these components and their proposed functions support the previous conclusions by Moher et al. (2014) and the present conclusions that distractor information, rather than target information, facilitated early visual attention in our task, the question remains: why do we see a memory component in the present results when the previous work from Moher et al. (2014) and the two distractor ERP experiment (above) did not find such a difference? One possibility is that because all of the previous work on this topic, including Zhang and Luck (2009), utilized a specific consistent attentional mapping for the roles of which color was the target and which were distractors (for a given participant), there would be minimal need to store these features in working memory. Since the present task had different distractor colors from trial to trial, it could be the case that this memory component is indicative of an inhibitory strategy of keeping these to-be-ignored distractor colors in working memory perhaps for the purpose of preparing for rapid disengagement from the distractors that are vying for attention (Moher & Egeth, 2012). Previous work has shown that the CDA (Vogel et al., 2005) and the SPCN (Zhang, Zhou, & Martens, 2009) can both be sensitive to items that are currently being ignored. Furthermore, our behavioral data analysis on the false alarm rate increasing as a function of distractor probes suggests that the more distractor probes that were

presented prior to a distractor dot cloud dimming on the attended side, the easier it is to ignore (and withhold a response to) the distractor dot clouds dimmings. If the Late Sustained Contralateral Positivity that we see is related to the distractor features being stored in working memory, as seems to be the case from our ERP results, then this could account for why we seen a reduction in false alarm rate as the number of prior distractor probe presentations: because the sustained memory signal from those probes allow for easier inhibition.

Finally, why do we see a positive increase in the P100 for the distractor probes compared to the target and neutral probes, which is the opposite directional difference that was found in both previous studies? The difference seems to be related to the current task demands, which are very different from the previous work. In all previous work on this paradigm, the relationship between the target and distractor information remained constant for a given participant. Furthermore, we showed in our transfer task above (i.e., the behavioral follow-up to the EEG/ERP TSD paradigm experiment) that the inhibition seems to be possible only in *relation* to the target feature. In the current task, since the distractor information is inconsistent (i.e., each participant had five possible distractor colors), but the target information remains consistent throughout the experience (i.e., only one possible target color was used per participant), this

change in the relationship between target and distractor weighting could be the reason we see a change in directionality. As with most (arguably, if not all) attentional ERP studies, it is hard to determine whether a directionality difference meaningfully represents excitation or inhibition from the ERPs alone. Rather, the important conclusion from this work, again, seems to be related to the categorical role that those features played in the task: that the distractor information seems to be playing a more critical role to the present attentional processes, compared to the target information which was treated statistically identically to the neutral information (which never showed up in the task at all).

Overall, our findings seem to demonstrate that even when distractor information is highly irregular, random, and is larger in quantity (i.e., more distractor colors than target colors), we don't see any evidence of target enhancement. Rather, if anything, we find evidence pointed at the contrary: that distractor feature information facilitates early feature-based attention even when it is unpredictable and highly irregular. Thus, it seems that these findings provide additional evidence to the power of inhibition in early feature-based attention.

Chapter 4: Learned Dietary Goals Influence Distraction by Energy-dense Foods

Chapter 4: Synopsis of Completed Experiments

Recent work in the field of attention has shown an increased interest in goal-driven attention. Specifically, as mentioned before there is a longstanding theoretical dichotomy between top-down attention and bottom-up attention (for review see Connor, Egeth, & Yantis, 2004; Kim & Cave, 1999; Wolfe, 1994), the former being influenced by the current goals of the participant and the latter being influenced by the physical traits of the visual stimulus, Awh, Belopolsky, & Theeuwes (2012) argue for an alternative framework, *goal-driven attention*. Specifically, they suggest that the old dichotomy fails to account for selection biases that cannot be explained by current goals or the characteristics in a visual scene. To better understand the dimensions of goal-driven attention, we must understand how goals, specifically goals that are learned over a lifetime, influence how humans select information in the visual world.

Much of the research investigating goal-driven attention utilizes goals developed through artificial training (e.g. red stimuli are worth $1.00). However, human lives are full of goals with a timeframe ranging from milliseconds to eons (i.e., evolutionary biases). Therefore, there appears to be a large gap in the

literature on whether the nature of a goal (e.g., its point in the timeline) influences attentional deployment in different ways and whether the mechanisms that support these natural, long-term, goal states function in different ways. What kind of natural goals, that are learned over a life time, might strongly influence attention?

High-fat foods are some of the most desirable foods due to their high palatability (Drewnowski, 1997). Previous work from the nutrition literature has found that images of energy-dense foods are highly attentionally demanding (Graham, Hoover, Ceballos, & Komogortsev, 2011; Werthmann et al., 2011). Additionally, results suggest that these attention effects are stronger for obese individuals with higher BMI (Castellanos et al., 2009). While these studies typically use paradigms that ask observers to attend to a centralized image on the screen, there is a lack of understanding of how energy-dense foods capture our attention when they are not the current goal in a task. Specifically, are energy-dense foods distracting in our daily life and, if so, how do learned goals related to eating energy-dense foods influence attentional prioritization?

The information that we attend to has a large impact on what we will learn from the world around us. Specifically, information that we learn, about foods in our

environment impacts our food choices and dietary intake, which in turn affects nutritional and health outcomes. Understanding the relationship between attention and food is especially important in light of the increasing rates of over-weight and obesity at all age levels in the US (Ogden et al., 2014). Addressing the neural and cognitive mechanisms of dietary behavior could also inform weight management interventions.

To investigate the role that dietary learning plays in distraction by energy-dense foods, I developed a novel distraction paradigm which borrowed elements from Forster & Lavie, (2011). In Experiment 6, we demonstrate that even when distractors are entirely irrelevant, participants were significantly more distracted by energy dense foods, compared to non-food objects and even low-fat foods. Additionally, in Experiment 7, we show the lability of these goal-states by having a separate set of participants consume a small amount of calorie-dense food prior to the task. The amount of distraction by the energy dense food images in this case was significantly reduced and no different than distraction by images of low-fat foods and images of non-food objects. In Experiment 8, we replicate the original findings but also examine whether the ingestion of energy-dense foods reduces attentional capture by all salient "interesting" stimuli. Our results demonstrate that the reduction in attentional capture after consuming calorie-

dense food is stimulus specific (i.e., only influences capture by energy-dense foods). The basis of this part of the chapter was recently accepted for publication in *Psychonomic Bulletin & Review.*

Title: The capture of attention by entirely irrelevant pictures of calorie-dense foods
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Abstract

Inborn preference for palatable energy-dense food is thought to be an evolutionary adaptation. One way this preference manifests itself is through the control of visual attention. In the present study, we investigated how attentional capture is influenced by changes in naturally occurring goal-states, in this case desire for energy-dense (typically high fat and/or high sugar) foods. We demonstrate that even when distractors are entirely irrelevant, participants were significantly more distracted by energy-dense foods, compared to non-food objects and even low-energy foods. Additionally, we show the lability of these goal-states by having a separate set of participants consume a small amount of calorie-dense food prior to the task. The amount of distraction by the energy-dense food images in this case was significantly reduced and no different than distraction by images of low-energy foods and images of non-food objects. While naturally occurring goal-states can be difficult to ignore; they are also highly flexible.

Introduction

Dietary behavior in humans is complex and controlled by a variety of factors (Drewnowski, 1997a, 1997b). More than two-thirds of adults in the United States are overweight or obese (Ogden, Carroll, Kit, & Flegal, 2014). A much smaller number suffer from binge-eating disorder, bulimia nervosa, or anorexia nervosa and are severely emaciated (Hoek, 2006). A growing body of research on these issues considers the role of cognition in understanding eating (e.g., Hall, 2016; Shafran, Lee, Cooper, Palmer, & Fairburn, 2007). One focus of such research is the attentional bias we have for energy-dense, typically high-fat and/or high-sugar, food.

Using variations of some standard cognitive tasks such as the dot probe task and various eye-tracking paradigms, previous research has shown an attentional bias for food over non-food objects, and, further, a bias for energy-dense food over food with little energy value (Mogg, Bradley, Hyare, & Lee, 1998; Van Dillen, Papies, & Hofmann, 2013; Werthmann et al., 2011). For example, Mogg et al. (1998) used a dot probe task to demonstrate that people have an attentional bias for food words compared to non-food words. In their task, they presented subjects with two words, one above a fixation cross and one below. In one case, one of the words was a food related work (e.g., sandwich) paired with a neutral,

unrelated non-food word (e.g., chair), in another case they presented a transport related word (e.g., airplane) and an unrelated neutral word. They presented the word pairs for a brief period of time, followed by a dot probe that appeared in the place of one of the words. The subjects were told to respond as quickly as possible to the location of the dot probe. They found that when subjects were hungry, they responded faster to dot probes that were in the same previous position as food words compared to dot probes in the same previous position as non-food words.

Recently, other researchers have used distraction paradigms as a way to better understand how food stimuli might distract us in the presence of other tasks. Critically, these studies are attempting to determine if food-related stimuli are more able to interfere with performance on an ongoing task than are non-food stimuli. Distraction paradigms test the ability of a subject to remain on task in the face of interference, that is, they involve executive control. The goal of that work has been to better understand the link between certain cognitive abilities and predilections and dietary outcomes (e.g., high BMI).

Lessons about distraction from the attentional capture literature

Some ideas relevant to the design of distraction experiments can be gleaned from the literature on attentional capture. Psychologists have been interested in

how attention is controlled for well over a century (e.g., James, 1890/1950). Early research was concerned with how internal factors such as expectation and intention controlled where attention was directed. Recently, external factors, such as stimulus salience or the suddenness of onset of a stimulus, have been the subject of intensive investigation. These two lines of research are now described as pertaining to "goal-directed" and "stimulus-driven" attention. Research on stimulus-driven attention suggests that attention may be captured by particular external stimuli, and that this capture may be unintentional and directly contrary to the subject's intentions (Bacon & Egeth, 1994; Graves & Egeth, 2016; Leber & Egeth, 2006; Theeuwes, 1994, 2010; Yantis & Jonides, 1984).

A major debate in the field of attention is concerned with the "automaticity" of attentional capture. An early critical example was provided by Folk et al. (1992). At the time conducted their experiments it had been well-established that a suddenly onset stimulus could attract attention, as could a salient singleton (e.g., the only red in a field of green elements) (Theeuwes, 1990; Yantis & Jonides, 1984). Folk et al. (1992) were interested in whether attentional capture was modulated by the feature similarity between the salient distractor (the captor) and the target item. Their studies used a variant of the spatial cuing paradigm.

In their first experiment, abrupt-onset cues produced a validity effect for sudden onset targets. That is, reaction time was faster when the target appeared in the same location that the cue had just appeared in than when it appeared in a different location. However, sudden onset cues had no such effect when the target was based on a color discontinuity. In their second experiment the cue was a color discontinuity (a red stimulus presented among several white stimuli). In this case the cue produced a validity effect for color-defined targets but not for abrupt-onset targets. Note that the cues in their experiments were statistically non-predictive of the location of the target or the correct response. For this reason, it seems reasonable to think of them as irrelevant distractors. (We keep the Folk et al [1992] terminology of "cue" here, to avoid confusion for readers familiar with their research.)

The double dissociation in the results of Folk et al. (1992) has been described as an example of contingent capture: attention is oriented toward (and perhaps captured by) non-predictive cues/distractors only when those cues/distractors are defined by features that match the defining features of the target. What this and subsequent studies made clear was that in order to determine whether capture by distractors is independent of attentional control settings, it is necessary to eliminate features from the potential distractor display that match

the defining features of the target (Bacon & Egeth, 1994; Folk et al., 1992; Folk, Remington, & Johnston, 1993).

Forster and Lavie (2008) made a serious effort to determine if attentional capture could be observed when target-defining features were eliminated from potential distractors. In their study, subjects were presented with visual search displays near the center of a monitor. On each trial, they had to indicate whether an N or an X was present in a background of several other letters. Subjects were requested to focus attention on this task. It was already known that letters presented in the periphery (and thus, due to their location, were task irrelevant) would interfere with task performance (e.g., Lavie, 1995). But letters are of the same category as targets and thus arguably, not totally irrelevant (see Lleras, Buetti, & Mordkoff, 2013 for an insightful discussion of this issue.) Therefore, Forster and Lavie (2008) presented on some trials a picture of an irrelevant cartoon character in the periphery. This stimulus slowed performance on the search task in a variety of conditions across three experiments. This result was taken to support the idea that attention could be captured by entirely irrelevant distractors.

Forster and Lavie (2008) had eliminated several target-defining features from their stimuli (e.g., the target was central, the distractor was peripheral; the target was alphanumeric, the distractor was pictorial). However, Gibson and Kelsey (1998) have demonstrated that subjects also monitor displays for features other than just local, target-specific features. In particular, subjects may be set to detect features that signal the onset of the task-relevant target display as a whole. For the Forster and Lavie (2008) experiment, this means that the fact that the search display and the distractor both onset at the same time stands in the way of considering the distractor being totally irrelevant to the task. To circumvent this problem, Forster and Lavie (2011) modified the procedure of their earlier paper. The central task involved successive judgments about a central matrix of letters and digits that remained static and visible for several seconds. During this time, dynamic (i.e., suddenly onset) peripheral distractor pictures were shown. They still interfered with performance, thus establishing that totally irrelevant distractors can capture attention, even when their onset is differentiated from that of the relevant stimuli.

Bridging the gap: combining attentional capture paradigms with studies on food distraction

The experiments described above point to critical methodological concerns that need to be addressed when we try to determine whether some stimulus class is acting as a distractor or is more distracting than some other stimulus class. It would appear that existing studies of distraction by food-related stimuli have not fully addressed these concerns. As an example, consider an adaptation of a method previously used to examine the distracting power of emotional stimuli, the attentional blink paradigm (e.g., Most, Chun, Widders, & Zald, 2005; Most, Smith, Cooter, Levy, & Zald, 2007; Most & Wang, 2011; Smith, Most, Newsome, & Zald, 2006). Specifically, in studies using the attentional blink paradigm in which the potentially interfering stimuli included pictures of food, accuracy of detection of the target picture was lower when the distractor stimulus was food than when it was a neutral stimulus (Neimeijer, de Jong, & Roefs, 2013; Piech, Pastorino, & Zald, 2010). Further, the magnitude of the effect depended on the subject's state of hunger (Piech et al., 2010). Although their results are both interesting and plausible, these studies use methods that create a task situation where the distracting stimuli share critical features with the target stimuli, and thus are relevant to the current goals of the participant.

Putting this more generally, in the attentional blink paradigm all stimuli (including the targets and distractors) are typically of the same type (e.g.,

colored pictures), characterized by sudden onsets, and share the same spatial location. It may not be possible to remove all such shared features (all stimuli, for example, are being shown in a laboratory), but one can at least try to maximize the distinctiveness of targets and distractors. To provide a strong test, experimenters should make the irrelevant stimuli as unrelated to the task as possible.

Our goal for the present experiments is two-fold. First, by adapting the previous paradigm from Forster and Lavie (2011), we presented participants with a novel task where the food images were truly irrelevant to the task at hand. Second, by varying the nutritional content of these irrelevant distractors we could address a gap in the literature that has failed to investigate whether all food that is irrelevant to the current task captures attention, or only foods that are the most desirable (again, something that would increase our understanding of food behavior in the real world).

To accomplish this, we assessed differences in the distracting power of images of energy-dense foods (e.g., high fat, high calorie), low-energy foods, and ordinary objects (see Figure 4.1) by adapting a variant of the task used by Forster and Lavie (2011). Specifically, subjects were shown a set of four

alphanumeric characters that they were to classify, one at a time, as digits or letters by pressing one of two response keys. At some time during the execution of this task, on a subset of the trials, a picture was shown; the picture was irrelevant to the classification task and no response of any kind was required to it. Note three key features of the task. First, by their natures the pictures and the alphanumeric characters were distinct, both semantically and perceptually. Second, they appeared in distinctive locations; the characters were central and the pictures peripheral. Third, the picture was not presented until the subject had already responded to the first of the characters. At that moment the suddenly-onset picture had dynamic properties, while the array of alphanumeric characters was static (Folk et al., 1993; Gibson & Kelsey, 1998). It has been shown that even when these three features are in place pictorial stimuli can capture attention (Forster & Lavie, 2011). The question we ask in Experiment 6 is whether the magnitude of attentional capture varies with the energy value of the stimuli depicted in the pictures. Finding that it does so vary, in Experiment 7 we explored the lability of the real-world goals that drive attentional capture and their dynamic relationship with attentional capture by giving subjects a small amount of energy-dense food to eat before they perform the experimental task. In Experiment 8, we aimed to replicate the key findings from Experiments 6 and 7, thus half of the subjects got a small amount of energy-dense food before the

experimental task and half did not. Furthermore, we wanted to extend those findings by testing whether consuming energy-dense foods decreases attentional capture to other attractive stimuli, or whether these effects were stimulus specific.

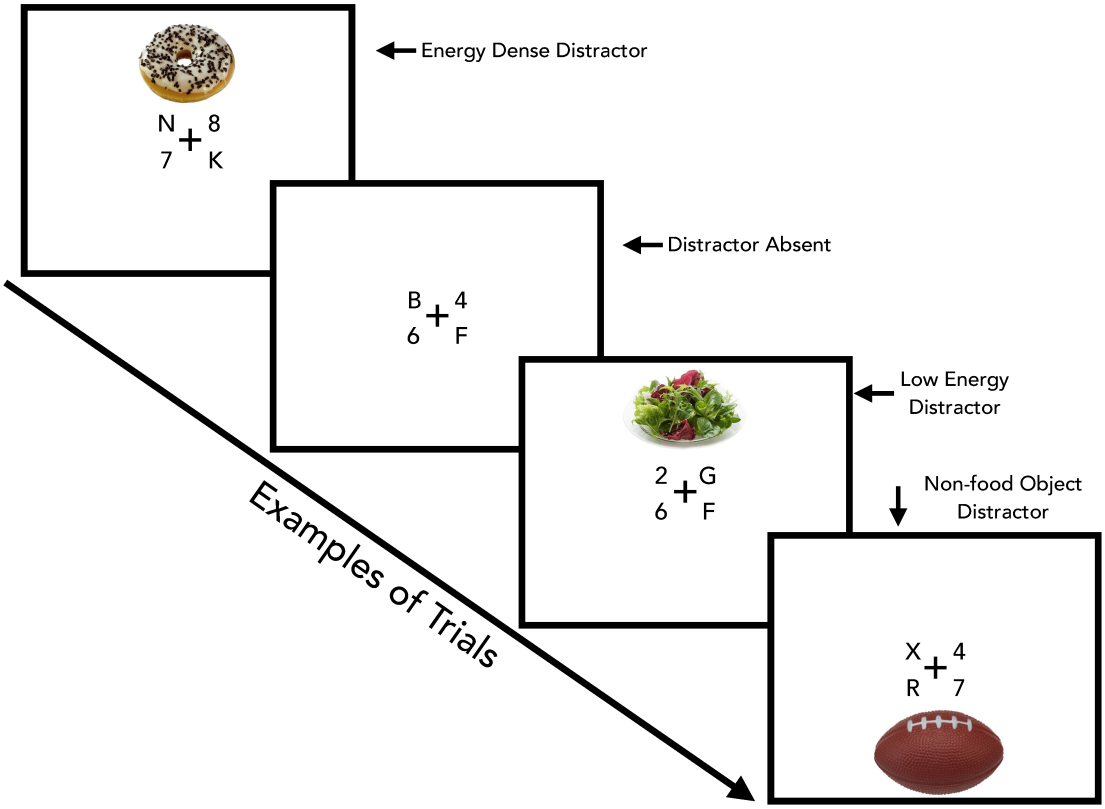

Figure 4.1 Design for Distractor Task for Experiments 6 and 7. Study design and sample stimuli. Observers were instructed to respond to each of the 4 symbols indicating, in order, whether each is a letter or number as quickly as possible. On 50% of trials, a distractor image randomly appeared prior to the 2nd, 3rd, or 4th response (never with the onset of the display). There were three types of distractor images: energy-dense food images, low-energy food images, and non-food object images. Every participant completed 600 trials. Note: Images are not to scale.

Experiment 6

Participants

We ran 18 Johns Hopkins University undergraduate students and community members (mean age = 19.4 years; 7 male, 11 female) with normal or corrected-to-normal visual acuity and normal color vision. We based our sample size on two criteria: (1) previous literature and (2) a power analysis. Previous work investigating attention and bias toward food images has used groups of 18 subjects to look at effects similar to ours (Castellanos et al., 2009). In addition, we conducted a power analysis using G*Power (Faul et al., 2007) which revealed that given an effect size of $\eta_p^2 = .14$, based on what related studies have previously found (e.g., (Veenstra, de Jong, Koster, & Roefs, 2010) , at least 18 participants would be required to have 95% power to detect the effect in our design. Research was performed with the approval of and in accordance with the Johns Hopkins Homewood Institutional Review Board. Informed consent was obtained from all participants in all experiments.

Apparatus

Experimental sessions were carried out on a Dell Precision T-3400 2.33-GHz computer. Stimuli were presented on a Dell 1708 FP monitor. Stimulus presentation was performed using programs written in MATLAB and using the PsychToolbox software (Brainard, 1997). The screen had a refresh rate of 60 Hz,

and the resolution of the screen was 1,280 × 1,024 pixels. Participants sat at a viewing distance of approximately 60 cm.

Stimuli

Each trial contained a matrix of 4 symbols surrounding a central fixation cross. The fixation cross subtended 0.5° of visual angle vertically and horizontally. Each of the four symbols was positioned in one of 4 quadrants around the fixation cross (see Fig. 4.1). The distance from fixation to the nearest part of a symbol was 2.2° of visual angle. Symbols subtended 0.5° by 0.8°. Finally, on a subset of trials distractor images would appear randomly above or below the central matrix for a brief time (125 milliseconds). These images subtended 5° to 9° horizontally and 6° to 9° vertically (with at least 1.5° between the distractor image and the nearest symbol).

Design and Procedure

On each of the 600 trials participants were presented with a centralized discrimination task, adapted from Forster and Lavie (2011). Each of the four items in the matrices shown in Fig. 4.1 are equally likely to be a letter or a number (chosen from 1-9 or X, R, T, J, L, P, N, F, B). Participants were shown

one matrix at a time and were instructed to report, in ordinary reading order, whether each symbol in the matrix is a letter or a number, responding as quickly as possible while also trying to be accurate. When a distractor image was presented, it appeared prior to the participants' response to the second, third, or fourth item. Thus the matrix on which the task was being performed was static while the distractor image had the dynamic property of sudden onset.

Distractors appeared on a random 50% of trials. For distractor-present trials, a third of these trials contained an image of energy-dense food, a third contained an image of a low-energy food, and a third contained an image of a non-food object. The order of presentation of all images was randomized. Images of food and objects were taken from the *Food.pics* database (Blechert, Meule, Busch, & Ohla, 2015). The database provides the macronutrient information for each image in the database, as well as physical image characteristics such as color composition, contrast, brightness, size, and complexity; this allowed us to control for any physical differences between distractor category sets. Images that were taken from this database were categorized into energy-dense foods, low-energy foods, and non-food objects, which were then compared on each of these physical characteristics using t-tests. All t-tests resulted in p-values > 0.05, indicating that these image categories did not differ from one another on these

physical image characteristics. Altogether there were 100 images of energy-dense foods, 100 images of low-energy foods, and 176 images of non-food objects available for the study. For each participant, we used all 100 images from the two food categories and 100 images, randomly selected for each subject, from the non-food category. Thus, for all distractor present trials, a novel distractor image was presented (avoiding any effects of familiarity). Participants completed 600 trials. Reaction times and accuracy on the task were recorded.

Data Analysis

We removed trials where reaction times that were more than 2 standard deviations above or below the mean per subject. This accounted for 4% on average across all experiments. We also removed trials on which subjects made errors on the digit-letter discrimination task; rates of such errors across all experiments were 4% on average. We also removed responses to symbols (within the four item matrix) where subjects made an error to the symbol immediately prior to a response. Due to the type of response in this paradigm, participants respond quickly to items within the matrix and if they incorrectly responded to an item due to a motor error (e.g., pressed the letter button but

they meant to press the number button), this might cause some delay on the subsequent button press. If a distractor was presented, this delay would appear to take longer due to distractor processing, but in reality, would reflect distractor processing plus the cost of processing the previous motor error. Therefore, we removed these trials, which accounted for 3% of trials. The first 10 trials of every session were considered practice and were removed.

We created an "attentional capture" score to assess the amount of distraction during the task. Specifically, we categorized trials into four types: energy-dense food distractor present, low-energy food distractor present, non-food distractor present, and distractor absent. We used response times on distractor absent trials as a reference point and subtracted those response times from the response times for the equivalent lag and position (recall that the distractor was never presented prior to the response to the first item, similar to Forster and Lavie, 2011) in each of the distractor present conditions. The remaining value is the reaction time cost of distraction for each of the distractor image types.

Results

As shown in Fig. 4.2 (black bars), participants in Experiment 6 were more distracted by images of energy-dense foods, than by images of non-food

objects and low-energy foods, suggesting that participants rapidly and implicitly assessed the nutritional value of the distractor images (Toepel, Knebel, Hudry, le Coutre, & Murray, 2009), even when they were entirely irrelevant.

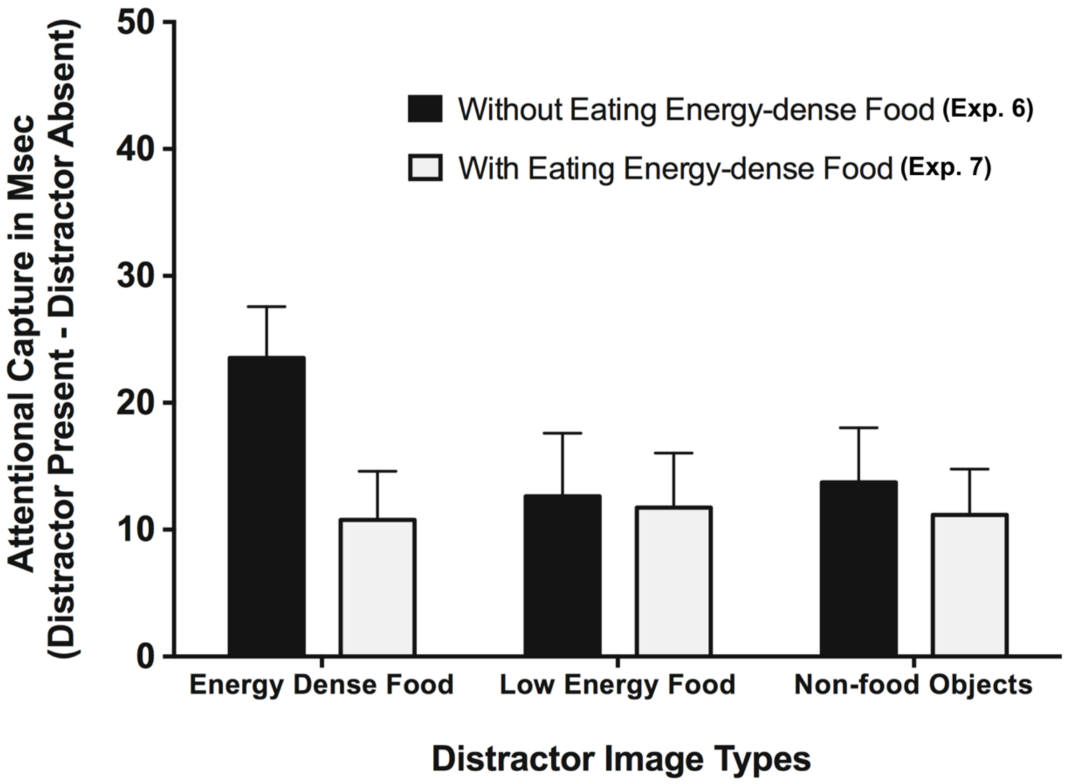

Figure 4.2 Attentional Capture by Irrelevant Images of Energy-dense Foods is Flexible. Results from Experiment 6 (black bars; without eating energy-dense foods) and Experiment 7 (gray bars; with eating energy-dense foods). The dependent variable (y-axis) is the amount of attentional capture for a given distractor type. This measure was calculated by taking the average reaction times when a distractor image was presented prior to a response (for each subject) and subtracting the baseline distractor absent reaction times (for each subject). Our results demonstrate that images of energy-dense foods are much more distracting than images of low-energy foods and images of non-food objects (*p*s < 0.05). However, when we had observers consume an energy-dense food prior to the study, the level of distraction of energy-dense food images was greatly reduced and this resulted in a significant interaction of image type and experiment ($p < 0.05$). Error bars are +/- 1 Standard Error of the Mean (SEM).

The differences evident in Figure 4.2 from Experiment 6 (see black bars) are

supported by the results of statistical analysis. We first conducted a one-way within-subjects ANOVA on the data from Experiment 6. We found a main effect of image type, $F(2,34) = 6.786$, $p = 0.003$, $\eta_p^2 = .29$, Geisser–Greenhouse corrected for nonsphericity. Additional post-hoc comparisons revealed that there was significantly more distraction by images of energy-dense foods compared to low-energy foods and non-food objects ($ps < 0.05$, Bonferroni corrected for multiple comparisons)[1]. Distraction by images of low-energy food and images of non-food objects did not differ ($p > 0.05$).

It is reassuring that the Food.pics database included physical characteristics for the images we used and that we were able to ascertain that there were no significant differences in color composition, contrast, brightness, size, or complexity among the three categories of stimuli we compared. However, that is not an exhaustive listing of visual features and so there was a lingering question about whether the striking difference we found in attentional capture scores might not be due to some other perceptual feature and not the

[1] To ascertain whether all of the classes of stimuli used created positive attentional capture, we ran two-tailed, one-sample t-tests on the scores in every condition for Experiments 6, 7, and 8 against the null hypothesis of zero effect. For Experiment 6 all ps < 0.025, for Experiment 7 all ps < 0.015, and for Experiment 8, all ps < 0.01. Thus, these results suggest all classes of stimuli caused some degree of attentional capture/disruption.

"meaning" of the pictures in terms of the fat content/energy density of the depicted stimuli. It struck us that it would be useful to manipulate some factor unrelated to the perceptual features of the stimuli that might be expected to influence the degree to which the energy-dense stimuli captured attention. Therefore, we decided to replicate Experiment 6, but with the addition that all subjects would be given a small snack immediately before participating. If it is the case that our difference in distraction is due to the hedonic value of energy-dense foods, we may be able to modulate that by changing the goal state related to these items by giving them some energy-dense food prior to the task.

Experiment 7

Participants

Similar to Experiment 6, we ran 18 Johns Hopkins University undergraduate students and community members (mean age = 19.2 years; 5 male, 13 female) with normal or corrected-to-normal visual acuity and normal color vision.

Methods

Experiment 7 was essentially identical to Experiment 6 with the exception that the 18 new subjects consumed their choice of two "fun sized" candy bars (each bar weighed about 17.3 g). The following candy bar types were used due to their high fat content: Snickers, Kit Kat, and Reese's Peanut Butter cups. The

average nutritional contents of two "fun sized" candy bars was 173.3 calories, 9.1g total fat, and 17.7g sugar. Candy bars were given to participants prior to participating in the task while they were filling out forms. Candy bars were completely consumed prior to the task.

Results

As shown in Fig. 4.2 (light gray bars), this separate set of participants in Experiment 7 was *not* more distracted by images of energy-dense foods, than by images of non-food objects and low-energy foods. A subsequent one-way within-subjects ANOVA revealed no main effect of image type, $F(2,34) = 0.062$, $p = 0.908$, Geisser–Greenhouse corrected for nonsphericity.

Experiment 7 was run after Experiment 6, and therefore, subjects were not assigned randomly to receive a snack or no snack before the test. Nevertheless, we were not aware of any obvious reasons why the subjects in the two experiments would have differed systematically (e.g., all subjects signed up for the studies in our university subject pool), and so we performed an overall analysis of variance combining the results of the two experiments.

We conducted a mixed-design two-way ANOVA that included the results of

both Exps. 1 and 2. There was a main effect of image type, $F(2,68) = 3.414$, $p = 0.04$, $\eta_p^2 = .09$, Geisser–Greenhouse corrected for nonsphericity, and, critically, a significant interaction between image type and experiment $F(2,68) = 4.517$, $p = 0.015$, $\eta_p^2 = .12$, Geisser–Greenhouse corrected for nonsphericity. Additional post-hoc comparisons on the interaction revealed that consuming the energy-dense food (Experiment 7) significantly decreased the amount of capture by images of energy-dense foods compared to not consuming the energy-dense food (Experiment 6). Specifically, we found that there was a statistically significant difference in the attentional capture scores for distraction by images of energy-dense foods when comparing across experiments (see the "Energy-dense Food" black and gray bars in Fig. 4.2, $p = 0.029$, Bonferroni corrected for multiple comparisons). This was supported by comparing the three image types within each experiment. For Experiment 6 (black bars in Fig. 4.2), there was significantly more distraction by images of energy-dense foods compared to low-energy foods and non-food objects ($ps < 0.05$, corrected for multiple comparisons). For Experiment 7 (gray bars), there were no statistically significant differences.

Experiment 8

In Experiment 8, we wanted to explore the limits of the effects found in Experiments 6 and 7 and replicate the key findings. In particular, we wanted to determine whether consuming energy-dense foods decreases attentional capture to other attractive stimuli, or whether these effects were specific to food-related stimuli. Previous research has demonstrated that emotional faces can capture attention (Hodsoll, Viding, & Lavie, 2011; Theeuwes & Van der Stigchel, 2006; Vuilleumier & Schwartz, 2001). Therefore, if consuming energy-dense foods generally reduces attentional capture by any interesting stimuli, we should see a differential effect for distractor images of emotional faces as well as energy-dense foods compared to non-food objects. Experiment 8 included distractor images of faces depicting fear and disgust which were taken from the Warsaw set of emotional facial expression pictures (Olszanowski et al., 2015). To keep the experiment acceptably short, we eliminated the low-energy food stimuli.

Participants

In Experiment 8 we ran two groups of 32 Johns Hopkins University undergraduate students and community members (mean age = 19.5 years; 15 male, 49 female) with normal or corrected-to-normal visual acuity and normal color vision. Using the results from the mixed analysis in Experiments 6 and 7, a

power analysis via G*Power (Faul et al., 2007) revealed that given an effect size of $\eta_p^2 = .09$, a minimum of 28 participants per group would be required to have 95% power to detect the effect in our design. As before, participants received extra credit in undergraduate courses or monetary payment as compensation, and all gave informed consent. The Johns Hopkins Homewood Institutional Review Board approved the protocol.

Methods

As the combination of Experiments 6 and 7 in a single analysis was not ideal, we ran the snack and no-snack conditions as a true experiment with subjects randomly assigned to the two conditions. Experiment 8 was similar to both Experiments 6 and 7 except the low-energy food image category was replaced with images of emotional faces. Additionally, there were several small changes in procedure from the preceding experiments; to enhance distraction, the distracting pictures were shown on 33% of the trials instead of 50% and the number of trials was reduced to 540.

Results

As shown in Fig. 4.3 (black bars), participants in Experiment 8 who *did not* consume the energy-dense food prior to the task were more distracted by

images of energy-dense foods, than by images of non-food objects and emotional faces. In contrast, when participants consumed the energy-dense food prior to the task, as shown further in Fig. 4.3 (gray bars), participants in Experiment 8 were *not* more distracted by images of energy-dense foods, than by images of non-food objects and emotional faces. The differences evident in Fig. 4.3 are supported by the results of statistical analysis. We first conducted a mixed-design two-way ANOVA. There was a main effect of image type, $F(2,124) = 3.281$, $p = 0.043$, $\eta_p^2 = .05$, Geisser–Greenhouse corrected for nonsphericity, and, again, a significant interaction between image type and whether or not subjects had an energy-dense snack before the test, $F(2,124) = 4.143$, $p = 0.019$, $\eta_p^2 = .06$, Geisser–Greenhouse corrected for nonsphericity. Additional post-hoc comparisons on the interaction revealed that consuming the energy-dense food (gray bars) significantly decreased the amount of capture by images of energy-dense foods compared to not consuming the energy-dense food (black bars). Specifically, we found that there was a statistically significant difference in the attentional capture scores for distraction by images of energy-dense food when comparing across the two groups of subjects (see the "Energy-dense Food" black and gray bars in Fig. 4.3, $p = 0.02$, Bonferroni corrected for multiple comparisons). This was supported by comparing the three image types within each group of subjects. For subjects who did not receive an energy-dense snack

(black bars in Fig. 4.3), there was significantly more distraction by images of energy-dense foods compared to non-food objects and emotional faces (ps < 0.05, corrected for multiple comparisons). While it was surprising that emotional faces were not any more distracting than everyday objects, this may be due to the effort that was made to make our pictures entirely irrelevant to the task at hand. Finally, for subjects who did get such a snack (gray bars), there were no statistically significant differences (*ps* > 0.05).

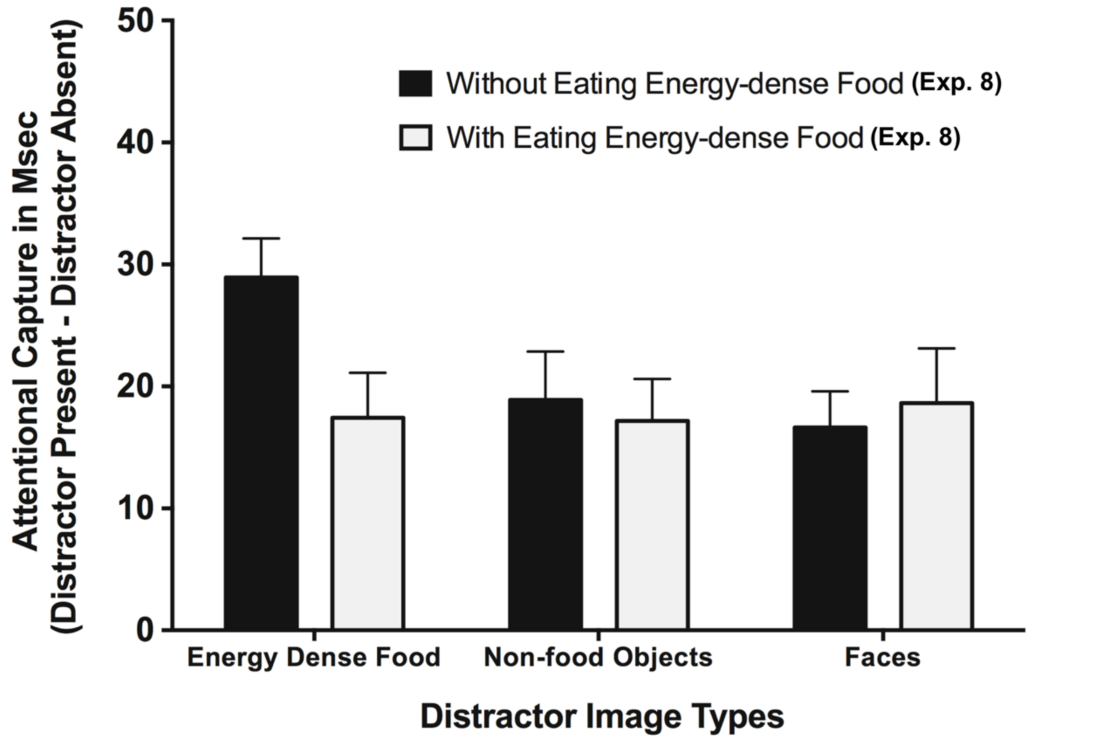

Figure 4.3 Naturally Occurring Goal-states Related to Energy-dense Foods are Flexible and Stimulus Specific. Results from Experiment 8. We replicated findings from Experiment 6 and 7. Additionally, the results demonstrate that images of energy-dense foods are even more distracting than images of emotional faces (*p*s < 0.05). When we had observers consume an energy-dense food prior to the study, we demonstrated that manipulating the goal-state associated with a particular stimulus is stimulus specific; we only found an effect of consuming energy-dense foods for distraction by images of energy-dense foods, resulting in a significant interaction ($p < 0.05$). Error bars are +/- 1 SEM.

General Discussion

Across all of our experiments, we have implied that the reaction time differences seen in our distraction task are due to "attentional capture." That is, attention is drawn to a distracting picture when it appears, and this interferes with performance on the central task. However, it has been argued that a shift of

spatial attention is just one way to account for reaction time costs due to distraction. Alternatively, some reaction time differences due to distraction may result from "filtering costs," which do not require a shift of attention to a distracting item, but rather, only a delay of the shift of attention to the relevant item, i.e., *a disruption and delay of attention* (e.g., Folk & Remington, 1998). One could argue that these disruption costs are not precisely attentional capture and that terminology should be reserved for spatially driven attentional effects. In any event, determining whether our effect is better described as capture or filtering cost is well beyond the scope of this paper (see Folk [2013] for the current state of this debate). Rather, the goal for this work has been from the beginning to determine whether when these interesting food stimuli are entirely irrelevant to the task at hand, they do cause some kind of disruption; whether that be spatially driven or some kind of delay and disruption. Importantly, these results demonstrate, for the first time, evidence for distraction by foods that have a higher energy density, even when they are entirely irrelevant to the current task. Critically, they are irrelevant in three distinct ways: (1) their semantic content (i.e., the main task involved responding to simple letters, not images), (2) their temporal properties (i.e., they showed up after participants had already begun responding the static central task), and (3) their spatial location (i.e., they never overlapped with any location that contained task relevant information).

Further, we demonstrate that even though these images are entirely irrelevant, these distraction effects are still sensitive to recent changes in goal-states (i.e., only distraction to the images of energy-dense foods were influenced by consuming candy).

It seems unlikely that the difference between energy-dense food and our other stimuli (food of low caloric density, objects, and faces) is due to bottom-up salience. For one thing, we were able to take advantage of the stimulus characterizations provided in the Food.pics database to control for many low level differences among distractor categories. For another, if perceptual salience were the key factor in the difference between calorie dense food and the other stimuli, it is difficult to see why ingesting a candy bar would eliminate that effect. Also, although we have no data on this point, it is worth doing the following thought experiment. Imagine a Kalahari bushman who has not had any contact with Western foods. Is there any reason to think that a picture of a pizza would be any more salient than a picture of a baseball, or a picture of a candy bar any more salient than a picture of a computer chip? These items are unfamiliar and, in the case of the two foods, there has been no opportunity for the development of motivational salience through the rewarding experience of

eating them (Nijs & Franken, 2012; Werthmann, Roefs, Nederkoorn, & Jansen, 2013).

While it seems reasonable to dismiss perceptual salience as a key factor, with real world stimuli like foods it is harder to figure out the relative roles of intentional top-down processes and reward history. Indeed, it seems likely that both may be operative (Lynn & Shin, 2015; Ristic & Landry, 2015). In this connection it is interesting to contrast the performance of our subjects with those in a study in which monetarily rewarded stimuli maintained their ability to serve as potent distractors for several months following the cessation of reward (Anderson et al., 2013). Why did ingesting a candy bar so quickly eliminate the greater attention-capturing power of energy-dense foods? Eating a candy bar amounts to just another "trial" in our life-long "training" on the rewarding effects of energy-dense food. Why should it decrease rather than increase attentional capture? The answer, obviously, has to do with motivational state (Piech et al., 2010; Robinson & Berridge, 2013). Recent research has shown that when an ordinarily rewarding stimulus (chocolate) is devalued, attention was no longer oriented toward reward-associated stimuli (Pool, Brosch, Delplanque, & Sander, 2014). Note, however, that devaluation in that case was accomplished by having subjects eat chocolate until they were satiated which, on average,

involved ingestion of 62.5 g of chocolate. This is substantially more the two small candy bars our subjects ate (approximately 30g).

More broadly, there is a substantial literature in which subjects are given "preloads" of food prior to behavioral testing to assess the effect on attention to food-related stimuli or to actual consumption of food (e.g., Herman & Mack, 1975; Branton et al, 2014). It is especially interesting that some investigations of the effects of preloads do not involve the actual consumption of food but are essentially cognitive manipulations such as arranging for subjects to see, smell, or think about palatable foods (e.g., Rogers & Hill, 1989; Papies, Stroebe, & Aarts, 2008; Jansen & van den Hout, 1991; Fishbach, Friedman, & Kruglanski, 2003). While the amount of palatable food we gave our subjects is on the low side for actual to-be-consumed preloads, it is obviously more than the amount given in the studies that used strictly cognitive manipulations.

It seems clear that it would be fruitful in future experiments to systematically manipulate motivational state (e.g., hours since eating), size of serving, as well as the nature of the "serving" (e.g., normal food, low calorie food, or mere visual or olfactory presence of food). Similarly, it would be useful to compare the effects of such manipulations on the bias towards foods (e.g., with dot probe or eye-

tracking studies), the distracting power of food-related stimuli (for example with the task presented in this paper), and the actual consumption of food, as these may not be controlled by the same mechanisms. Finally, individual differences, in particular, the extent to which subjects may be categorized as normal or restrained eaters, should be considered, as the effects of preloads have been shown to be markedly different for these groups (e.g., Herman & Mack, 1975; Rogers & Hill, 1989).

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Author Contributions

Both authors contributed to the study design. Testing and data collection were performed by C.A.C.. C.A.C analyzed and interpreted the data under the

supervision of H.E.E.. C.A.C. drafted the manuscript, and H.E.E. provided critical revisions. Both authors approved the final version of the manuscript for submission.

Chapter 5: Redefining A Common Neural Marker of Attention

Chapter 5: Synopsis of Completed Experiments

The use of electroencephalography (EEG) to derive event-related potential (ERP) components for specific attentional events has become an increasingly popular method for investigating cognitive processes that are difficult to probe with only behavioral techniques. The N2pc is one component that has become a common measure for cognitive neuroscientists to establish attentional selection in a variety of experiments. In fact, many fields beyond psychology and neuroscience, such as clinical neuropsychology and medicine more broadly, have begun to use this component to better understand attentional processes. Since the classic study of Woodman and Luck (1999), this component is typically considered to represent the neural marker for shifts of spatial attention across space. However, the current findings from our study clearly demonstrate that the N2pc cannot reflect *just* an initial shift of attention, but in fact it reflects (1) only post-selection processing well beyond the initial shift of attention or (2) post-selection processing plus the initial shift of attention. To demonstrate this, we conducted two ERP experiments (the second is a replication of the first, with additional controls). In our experiments, we had participants complete a visual detection task for a target stimulus (the letter E) and they were instructed to only

responded if it was present in the display. Critically, some displays only contained a similar distractor stimulus (the letter F which is similar to the target letter E) and some displays only contained a dissimilar distractor stimulus (the letter Q). If the N2pc were to reflect the initial shift of attention to a stimulus prior to any processing of that stimulus, then we should see similar N2pc waveforms (and amplitudes) for all conditions. However, if the N2pc were to reflect post-selection processing, this should result in different N2pc amplitudes depending on what stimulus was shown and how similar it is to the target stimulus. Importantly, we found that the N2pc showed a graded amplitude that decreased as a function of how similar the current stimulus was to the target item, where the largest amplitude occurred when the target was presented, followed by the similar distractor stimulus, and, lastly, the dissimilar distractor stimulus. Rather than representing just a shift of spatial attention, these results demonstrate that the N2pc also must reflect some form of post selection processing. Importantly, while we can show that there is some post-selection processing taking place, with typical N2pc paradigms like these and the nature of measuring ERPs we are unable to disentangle whether the N2pc solely reflects post-selection processing vs. post-selection processing plus some activity from the initial shift of attention. However, our goal for this work was only to demonstrate that a reframing of the cognitive processes that were

originally attributed to the N2pc (i.e., that it represents an initial shift of attention) is necessary.

Title: Redefining A Common Neural Marker of Attention

In review at Psychonomic Bulletin & Review

Abstract

The use of electroencephalography (EEG) to derive event-related potential (ERP) components for specific attentional events has become an increasingly popular method for investigating cognitive processes that are difficult to probe with only behavioral techniques. The N2pc is one component that has become a common measure for cognitive neuroscientists to establish attentional selection. In general, this ERP component has become synonymous with an initial shift of attention. However, the large body of work utilizing the N2pc has yet to establish whether, in fact, it reflects the underlying cognitive processes related to an initial shift of attention or whether this component actually reflects a whole host of additional attentional processes that occur after selection. Here we examine the nature of the N2pc component by specifically probing whether the N2pc also reflects post-selection processing rather than just an initial shift of attention. While recording EEG, we had participants perform a visual detection task where we varied the similarity between a target stimulus and other non-target stimuli. Our results revealed that the N2pc showed a graded amplitude that decreased as a function of how similar the current stimulus was to the target

item, where the largest amplitude occurred when the target was presented. These findings suggest that the N2pc must reflect either only post-selection processing occurring after an initial shift of attention, or at the very least the initial shift of attention plus post-selection processing.

Significance Statement

To understand the underlying structure of processes involved in human visual attention, we need to understand how (1) information is initially selected and (2) how that information is subsequently processed. Recently, new advanced in electrophysiological measures have lead researchers to depend on a particular event-related potential component (i.e., the N2pc) as a neural marker of the initial shift of attention to a visual stimulus. While it has been widely accepted that this component reflects such properties, it has yet to be directly tested. Our findings show that this component cannot solely reflect the initial shift of attention, but rather, it reflects subsequent processing after that initial selection.

Introduction

Visual attention is inherently capacity limited. While it may *feel* like we have conscious access to all of this visual input at once, in fact there is actually a limited subset of information we can process in a given moment. Among other things, this is why it is recommended to not text on a cellphone while driving. The primary limiting factor of attentional processing is *selection*. In order to process information, we must first select that visual input and then subsequently process it. In fact, it has been shown that in order to bind a group of features into an object, for identification, *selection* is required (Treisman & Gelade, 1980).

While there has been a long standing debate about the nature of selection since William James (James, 1890/1950), more recently some of the debate has turned to understanding the neural mechanisms underlying this attentional process (Eimer & Kiss, 2010; Theeuwes, 2010). The use of electroencephalography (EEG) to derive event-related potential (ERP) components for specific attentional events has become an increasingly popular method for investigating attentional processes that are difficult to probe with only behavioral techniques. The N2pc is one such component that has become a common measure for cognitive neuroscientists to establish attentional selection in a variety of experiments (for example see (Eimer, 1996; Luck &

Hillyard, 1994b; Mazza, Turatto, & Caramazza, 2009a)). Since the classic study of Woodman and Luck (Woodman & Luck, 1999), this component is typically considered to represent the neural marker for shifts of spatial attention. Moreover, it has been strongly argued that the N2pc not only occurs when there is a shift of spatial attention, but specifically it occurs when there is an *initial* shift of attention to a visual stimulus (Eimer & Kiss, 2007; Leblanc, Prime, & Jolicoeur, 2008; Woodman & Luck, 1999). However, this characterization of the N2pc component has recently become the focus of theoretical debate (Eimer & Kiss, 2010; Theeuwes, 2010). In contrast to the common interpretation that the N2pc reflects an initial shift of attention, we hypothesized that the N2pc is actually indicative of post-selection processing at the location of a visual stimulus. Here, we utilized EEG and behavioral measures (i.e., a visual detection task) across two experiments to investigate the nature of this component. Specifically, we developed a visual detection task (see Figure 5.1, upper left) that contained a to-be-identified object paired with a placeholder item on each trial (note: the to-be-identified object was lateralized on two-thirds of trials which is the kind of display organization that is typically used to measure the N2pc). Participants were instructed to search for a target object (i.e., the letter "E") and to respond as quickly as possible if it was presented. Critically, the to-be-identified object could be: (1) the target object, (2) a similar distractor (i.e., the letter "F"), or (3) a

dissimilar distractor (i.e., the letter "Q"). If it is the case that the N2pc does not reflect just an initial shift of attention, but rather reflects either post selection processing, or an initial shift plus post selection processing, then we should see that the N2pc is sensitive to modulations in the similarity between the current attentional template (i.e., what participants were looking for) and the presented stimulus.

Results

In Experiment 9, we presented participants (n=40, 18 male, ages 18-22, mean age = 20, one subject was removed due to a technical error) with a visual search task where they were instructed to search for the letter "E" (either mirrored or in the normal orientation) (see Figure 5.1, upper left). Critically, we had three types of trials: trials that contained the target stimuli, trials that contained a similar distractor stimuli (either a normal or mirrored "F"), and trials that contained a dissimilar distractor stimuli (either a normal or mirrored "Q"). Participants were asked to make a speeded response when they detected the letter "E" and to withhold a response for any other letter.

Behavioral Results from Experiment 9

As shown in Figure 5.1 (lower left), we found that overall participants were very good at the task (average percent correct for target present trials was 98%). Crucially however, we found evidence that demonstrates that the manipulation of distractor similarity worked: correct rejections for similar distractor trials (when an "F" was present) were significantly lower, $t(38) = 3.42$, $p < .002$, than those for dissimilar distractor present trials (when a "Q" was present). Specifically, this suggests that participants found it much harder to withhold a response to the distractor "F" presentations compared to the distractor "Q", suggesting that participants did in fact perceive the F to be more similar to the E.

EEG Results from Experiment 9

To investigate the effect of our stimulus condition (i.e., the different letters presented) we conducted a repeated measures one-way ANOVA for the mean amplitudes in the N2pc time window. As shown in Figure 5.1 (right side), our analysis revealed a main effect of stimulus condition, $F(2,76) = 18.75$, $p < 0.001$, $n_p^2 = 0.33$. Subsequent pairwise comparisons demonstrated that N2pcs to all three conditions are different from one another, ps < 0.03 (Bonferroni corrected). Importantly, we see in Figure 5.1 that the magnitude of the N2pc is in the order that would suggest post-selection processing: the largest N2pc is for trials that contain the target, followed by those that contain the similar

distractor, and then the lowest magnitude is for the dissimilar distractor. If the N2pc were indicative of only an initial shift of attention these N2pc amplitudes should all be similar.

In addition to our N2pc findings, we also found a main effect across stimulus conditions for the sustained posterior contralateral negativity (SPCN) which has been suggested to reflect the encoding of stimulus information into visual working memory (Fahrenfort et al., 2017). For the SPCN time window we see a significant effect of the stimulus condition, $F(2,76) = 5.07$, $p = 0.01$, $n_p^2 = 0.12$. Critically, pairwise comparisons revealed that the averaged mean amplitude in dissimilar distractor Condition was significantly different from target Condition, $p = .016$ (Bonferroni corrected). Additionally, there was a slight trend suggesting that the SPCN was different for the dissimilar distractor Condition compared to the similar distractor Condition, $p = .089$ (Bonferroni corrected). This suggests that the participants may even have encoded whether these items were or weren't the target (and that the similarity of the "E" vs. "F" conditions made that decision difficult).

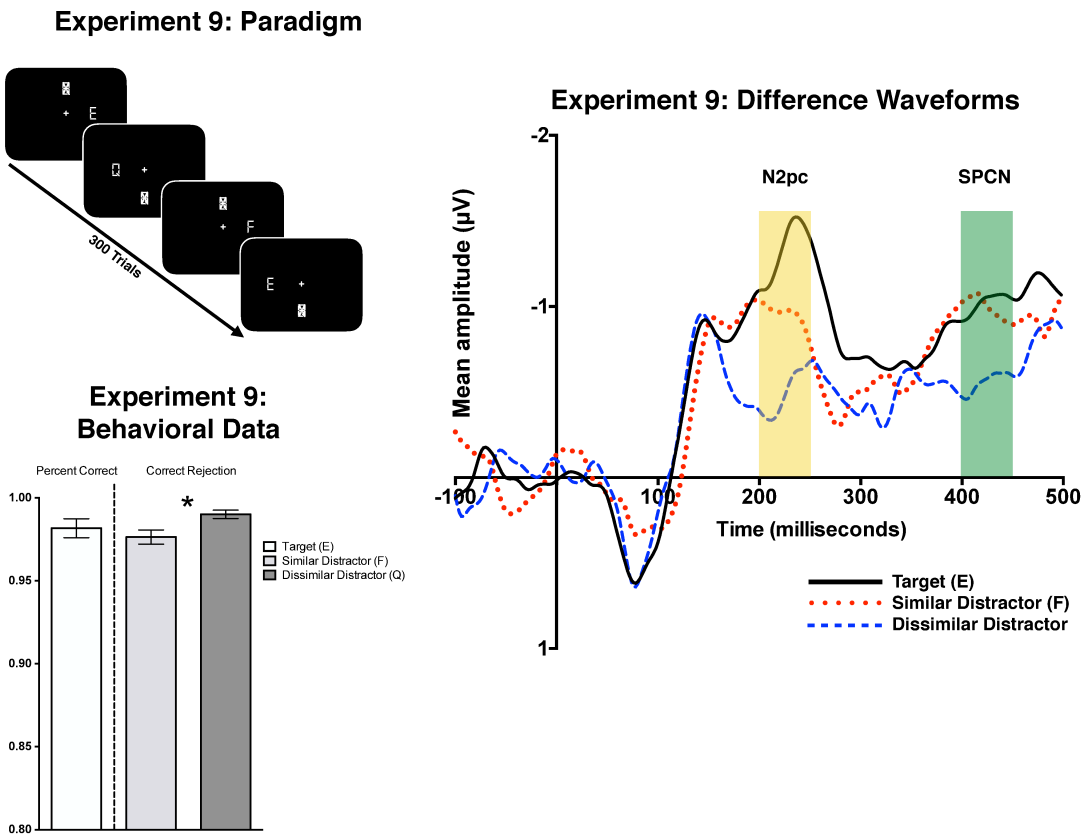

Figure 5.1 The design and results from Experiment 9. Upper Left: The paradigm for Experiment 9. Each trial consisted of a fixation cross that would appear for 250 milliseconds which was then followed by the presentation of a stimulus display. The stimulus display onset was randomly jittered to avoid entrainment. All stimulus displays consisted of a fixation cross in the center, one letter, and a placeholder. The critical letters included "E", "F", or "Q" and the placeholder consisted of other randomly drawn letters that were overlaid on one another. Subjects were instructed to search for a capital letter "E". If they found the capital "E", they were instructed to press a response button on a gamepad as quickly as possible. If any other non-target letter was presented (either "F" or "Q"), they were instructed to withhold a response. The stimulus display was presented for 1000 milliseconds. Reaction times and accuracy were recorded. Position of the placeholder and letter were randomly chosen such that roughly two-thirds of trials contained trials where the placeholder was on the vertical axis (either the 0° or 180° positions) and the letter was presented on the horizontal axis (either the 90° or 270° positions). The other one-third of trials contained trials where the letter was on the vertical axis (either the 0° or 180° positions) and the placeholder was presented on the horizontal axis (either the 90° or 270° positions). This setup was chosen to maximize analyzable trials for the N2pc (see Methods). Participants were told to make a response as quickly as possible when they saw the letter "E". If another letter was presented (either a similar distractor "F" or a dissimilar distractor "Q") they were told not to respond. Lower Left: Response accuracy for the different letter conditions. Critically, correct rejections for the similar distractor letter were significantly lower than for the dissimilar distractor letter ($p < 0.002$). Right Side: ERPs for the different letter conditions. N2pcs were significantly different across all three conditions ($ps < 0.03$, Bonferroni corrected).

Overall, the results from this initial experiment provide strong evidence supporting the notion that the N2pc is a ERP component that does not reflect the initial shift of attention to a particular stimulus, but rather it reflects post-selection processing, or at the very least the combination of the two processes. However, since the N2pc is a lateralized component it might be the case that since our displays in Experiment 9 used a mid-line placeholder with a single lateral stimulus (e.g., (Hickey, Di Lollo, & McDonald, 2009)) this could have influenced the N2pc in an unanticipated manner.[2] Therefore, to replicate our effects from Experiment 9 and to address issues of laterality, we ran an additional experiment where the stimulus and the placeholder were always lateralized (each randomly placed on the left and right respectively).

Behavioral Results from Experiment 10

In Experiment 10, we presented participants (n=32, 8 male, ages 18-25, mean age = 20) with a similar task to Experiment 9, except both the stimulus and placeholder for every trial were lateralized (see Figure 5.2, upper left). As shown in Figure 5.2 (lower left), we again found that, overall, participants were very good at the task (average percent correct for target present trials was 99%). We

[2] We would like to thank Martin Eimer for feedback and suggestions on this initial study.

again found corroborating evidence that demonstrates that our distractor similarity manipulation still worked: correct rejections for similar distractor trials (when an "F" was present) were significantly lower, $t(31) = 2.91$, $p < .007$, than those for dissimilar distractor present trials (when a "Q" was present).

EEG Results from Experiment 10

To investigate the effect of stimulus condition, we again conducted a repeated measures one-way ANOVA for the mean amplitudes in the N2pc time window. As shown in Figure 5.2 (right side), our analysis revealed a main effect of stimulus condition, $F(2,62) = 16.94$, $p < 0.001$, $n_p^2 = 0.35$. Subsequent pairwise comparisons again revealed that N2pcs in all three conditions are different from one another, ps < 0.03 (Bonferroni corrected). Additionally, we again see that in Figure 5.2 that the magnitude of the N2pc is in the order that we predicted: the largest N2pc is for trials that contain the target, followed by those that contain the similar distractor, and then the lowest magnitude is for the dissimilar distractor. Finally, we again found a main effect across stimulus conditions for the SPCN time window, $F(2,62) = 6.22$, $p = 0.007$, $n_p^2 = 0.17$. Critically, pairwise comparisons revealed that the averaged mean amplitude in the dissimilar distractor condition was significantly different from the target condition, $p = .034$ (Bonferroni corrected). Additionally, the dissimilar distractor condition was

significantly different from the similar distractor condition, p = .014 (Bonferroni corrected).

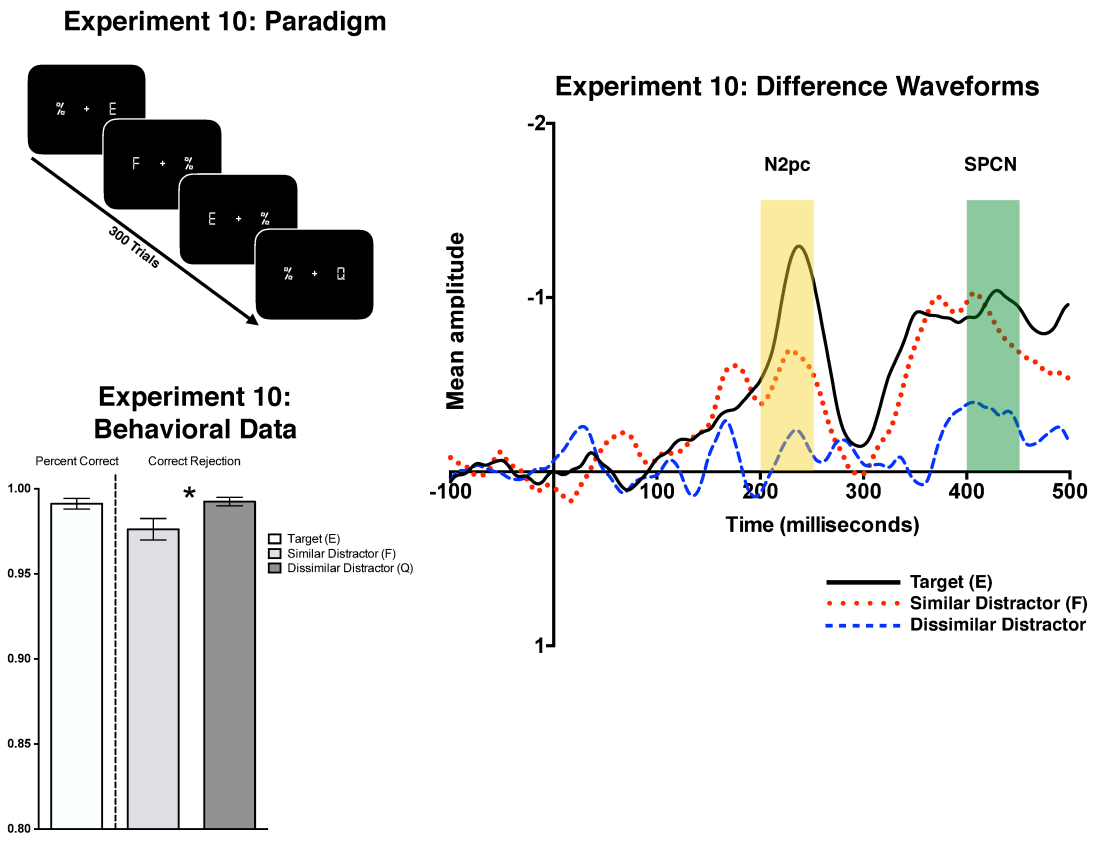

Figure 5.2 The design and results from Experiment 10. Upper Left: similar to Experiment 9, the trials consisted of a placeholder and a critical letter. In this experiment, we lateralized all items on every trial. Lower Left: Response accuracy for the different letter conditions. Again, correct rejections for the similar distractor letter were significantly lower than for the dissimilar distractor letter ($p < 0.007$). Right Side: ERPs for the different letter conditions. N2pcs were again significantly different across all three conditions ($ps < 0.03$, Bonferroni corrected).

General Discussion

Across two experiments, we found evidence suggesting that the N2pc does not simply reflect the underlying cognitive processes associated with an "initial shift

of attention," rather our findings support the notion that the N2pc corresponds to deeper, post-selection processing of the already attended stimuli. In our experiments, we created a situation where the observer needs to identify a laterally presented letter to determine whether they should respond to it (if it was a target letter) or whether they should withhold a response (if it was a distractor letter). Since observers would need to attend to these items to bind the features for identification (Treisman & Gelade, 1980), the initial selection of each of the letters should be similar. Rather, if the N2pc reflects changes in post-selection processing and further post-selection processing is required to differentiate a target letter from distractor letters, and a target letter from similar distractor letters, then we should see that the N2pc amplitudes are different depending on our letter conditions. This is exactly what we found. Critically, even if we compare just our two distractor letter conditions (i.e. F vs. Q) where no motor response was required, we still see that those conditions differ from one another. Therefore, these differences cannot be due to differences in response type, rather they have to do with the content of the stimulus and, more importantly, the similarity of those distractor letters to the target letter. It is important to note that we are not arguing that the N2pc does not reflect any selection of the attended item. In fact, there very well could be an underlying signal in that time-window that reflects the initial selection of the item, followed

by the post-selection processing. The important distinction here is that within the N2pc time-window, for a typical N2pc, we are seeing *differential activity* that is more in line with differences in processing. Importantly, while we can show that there is some post-selection processing taking place, with typical N2pc paradigms like these and the nature of measuring ERPs we are unable to disentangle whether the N2pc *solely* reflects post-selection processing vs. initial selection activity + post-selection processing. However, for this study our goal was only to demonstrate that a reframing of the cognitive processes that are attributed to the N2pc (i.e., an initial shift of attention) is needed.

The relationship between the N2pc and the Pd

In recent work, many researchers have used the relationship between the N2pc and the Pd, a component thought to indicate attentional suppression, to investigate the interplay of attending to target information (e.g., N2pc activity) while simultaneously ignoring distractor information (e.g., Pd activity) (Sawaki, Geng, & Luck, 2012). Much of the literature has shown that the timing window of the N2pc and the Pd are relatively close (Kiss, Grubert, Petersen, & Eimer, 2012; McDonald, Green, Jannati, & Di Lollo, 2013), and in some cases, the timing directly overlaps (Sawaki et al., 2012). In the present work, should we expect suppression (i.e., a Pd) of the stimuli? Moreover, are the differences that we see

due to hidden Pd activity driving down the N2pc response? We believe there is no reason to expect suppression in our displays. Specifically, the Pd shows up in response to a distractor being suppressed which reduces attentional competition (i.e., biased competition (Desimone & Duncan, 1995)), thus allowing the target to have a more differentiated attentional signal. Across all of our displays there is only one letter item to select, and thus little to no competition to resolve. Additionally, while there was a placeholder in all of our displays, we presented the exact same one across all conditions. Thus, if participants were suppressing that item it should be consistent for conditions, which would not explain our current findings. Another critique of our claims might be that some kind of differential suppression is occurring for the letter item in our displays within the same time window as the N2pc and this is actually what is creating differentiated N2pcs across our conditions. While this wouldn't be in line with any previous findings on the N2pc, this would also mean that all previous N2pc work would be susceptible to this criticism (i.e., even if the waveforms are similar, there could be underlying differences). However, this critique would actually still support our claim that something besides the initial shift of attention is occurring during the N2pc, and that this ERP time-window and component actually reflect *post-selection processing*. However, it is important to note that none of our contra-ipsi waveforms show any evidence of a Pd.

Neural evidence supporting the N2pc being associated with post-selection processing

Past work in humans using EEG (Luck, Girelli, McDermott, & Ford, 1997) and magnetoencephalography (MEG) (Hopf et al., 2000) have suggested that activity associated with the N2pc has been localized to area V4 and higher ventral visual areas. In contrast to these studies, there has also been substantial work demonstrating that neural evidence of selection can occur in much earlier visual areas, such as V2 and even some hints of activity in V1 (Luck, Chelazzi, Hillyard, & Desimone, 1997). Furthermore, prior work in humans has shown that attention can already play a critical role as early as 100 milliseconds (Moher et al., 2014; Zhang & Luck, 2009). Specifically, it has been shown that there are differences in P100 activity for attended-to and to-be-ignored stimuli. The P100 is an ERP component that reflects the early initial wave of feedforward processing (Mangun et al., 1998; Woldorff et al., 1997). Thus, one possible ERP component that might reflect this initial shift of attention could actually be the P100. While the current study does not address this, past work (Moher et al., 2014; Zhang & Luck, 2009) does provide evidence that this might be the case.

Conclusion

Taken together, the results from these two studies demonstrate that the N2pc might not simply reflect a shift of spatial attention, rather the N2pc reflects some form of post-selection processing occurring *after the initial shift of attention*. The current findings advance our understanding of the underlying temporal structure of attentional processing and, in particular, the neural correlates that we have assigned to the processes that make up that structure. However, these current results do not diminish the value of the N2pc as a tool for understanding attention; instead as a field we need to reexamine the processes that have been attributed to this component and understand how those findings might reflect post-selection processing of attended stimuli.

Methods

Experiment 9

Participants

Forty participants (18 male, ages 18-22, mean age = 20) took part in EEG experimental sessions lasting around 1 hour. Participants were undergraduates from Johns Hopkins University who participated in the study for extra credit in undergraduate courses. One subject was removed due to a technical error during recording. All participants reported normal or corrected-to-normal vision. Research was performed with the approval of and in accordance with the Johns

Hopkins Homewood Institutional Review Board. Informed consent was obtained from all participants in all experiments.

Stimuli and Procedure

The experimental sessions were performed in a dimly lit, sound-attenuated, and electrically shielded experimental booth. Stimuli were shown using an Epson PowerLite Home Cinema 3000 projector. Stimuli were back projected through a hole outside the room onto a 76 cm x 76 cm projector screen inside the room. The pixel screen resolution was set to 1024 x 768, which resulted in a projected screen size of approximately 36 cm by 27 cm. Stimulus presentation, timing, and response recording were controlled by a Dell PC running under Windows, using Psychtoolbox (Brainard, 1997) for Matlab (Mathworks, Inc).

The screen was set at an approximate viewing distance of 70 cm from the seated participant. The fixation cross in our experiments subtended a visual angle of approximately 0.65° by 0.65° degrees. All placeholder and letter stimuli subtended an approximate visual angle of 1.47° by 0.98°. In Experiment 9, stimuli could appear in one of four locations (surrounding fixation) at 0°, 90°, 180°, and 270° from vertical. The center of the stimulus was approximately 8.6

degrees away from the center of fixation. All stimuli were shown in the color red (RGB= [255 0 0]) and were presented on a black background (RGB = [0 0 0]).

The beginning of each trial started with a black screen that was shown for 250 milliseconds. A fixation cross would appear after the 250 milliseconds which was then followed by the presentation of a stimulus display. The stimulus display onset was randomly jittered to avoid entrainment; therefore, it could appear randomly between 200-700 milliseconds after the fixation was presented. All stimulus displays consisted of a fixation cross in the center, one letter, and a placeholder. The critical letters included normal and mirrored versions of: "E", "F", or "Q". In Experiment 9, the placeholder consisted of other randomly drawn letters that were overlaid on one another (see Figure 5.1 for an example). Subjects were instructed to search a capital letter "E" that was either normal or mirrored. If they found the capital "E" in either its normal or mirrored form, they were instructed to press a response button on a gamepad as quickly as possible. If any other non-target letter was presented (either "F" or "Q" normal or mirrored), they were instructed to withhold a response. The stimulus display was shown for 1000 milliseconds. Reaction times and accuracy were recorded.

There were 300 trials total. Half of the trials had a target "E" present and half had a non-target present ("F" or "Q"). In half of all trials the letter was presented in the normal orientation and the other half of trials the letter was presented as a mirrored image. Position of the placeholder and letter were randomly chosen such that roughly two-thirds of trials contained trials where the placeholder was on the vertical axis (either the 0° or 180° positions) and the letter was presented on the horizontal axis (either the 90° or 270° positions). The other one-third of trials contained trials where the letter was on the vertical axis (either the 0° or 180° positions) and the placeholder was presented on the horizontal axis (either the 90° or 270° positions). These trials were not analyzed because, due to the lateralized nature of the N2pc component, we would be unable to measure any N2pcs to any of the critical items. They were merely included to create variety in the task so that participants did not become entrained to our critical trials.

EEG Recording and Data Analysis

EEG data was recorded using an actiCHamp amplifier (BrainVision) with 32 Ag/AgCL channels. EEG data were sampled at 500 Hz. Data were online referenced to Cz and later were offline referenced to the average of the left and

right mastoids. Eye movements were measured through the two frontal eye channels (FP1 and FP2).

All EEG and ERP data analyses were conducted through EEGLAB (Delorme & Makeig, 2004) and ERPLAB (Lopez-Calderon & Luck, 2014) toolboxes for Matlab. Timing of the stimulus presentation and event codes were corrected using a photodiode. Trials with eye movements, eye blinks, or excessive muscle movements were excluded from the analysis. Epochs began 100 milliseconds before the stimulus presentation and ended 500 milliseconds after the beginning of the presentation. Artifact free ERPs were time-locked to the presentation of the stimulus display. ERPs were digitally low-passed filtered (-3dB cutoff at 30 Hz) separately for each subject. ERPs were averaged separately for each stimulus condition. Since we were interested in the N2pc and it is a lateralized component, we only used trials where the placeholder was on the vertical meridian and the letter stimulus was presented in one of the two horizontal positions. For each condition, we then collapsed across the horizontal presentations of the letter stimulus (left or right) and the lateral position of the electrodes to allow us to create waveforms that were recorded contralaterally and ipsilaterally to the presentation of the letter stimulus. For each participant, mean N2pc and SPCN amplitudes were measured at six lateralized posterior

electrodes (P3/P4/P7/P8/O1/O2), consistent with existing data on the location of these components(Mazza, Turatto, & Caramazza, 2009b). For all experiments, the N2pc mean amplitude was measured from 200–250 millisecond post-stimulus onset (consistent with the typical time window for this component e.g., (Brisson, Leblanc, & Jolicœur, 2009)) and the SPCN mean amplitude was measured from 400–450 millisecond post-stimulus onset (also consistent with the typical time window e.g., (Prime & Jolicoeur, 2010)).

Experiment 10

Participants

Thirty-two participants (8 male, ages 18-25, mean age = 20) took part in EEG experimental sessions lasting around 1 hour. Participants were undergraduates from Johns Hopkins University who participated in the study for extra credit in undergraduate courses. All participants reported normal or corrected-to-normal vision. Research was performed with the approval of and in accordance with the Johns Hopkins Homewood Institutional Review Board. Informed consent was obtained from all participants in all experiments.

Stimuli and Procedure

The setup for Experiment 10 was almost identical to Experiment 9, but with the following changes: First, we changed the positioning of all stimuli such that on every trial both items were presented horizontally (the 90° and the 270° degree positions). The position of the placeholder and the letter (either on the left or right side of the screen) was randomly balanced. As stated above, this was due to concerns that having uneven visual information on one side of the screen would influence the N2pc waveform in undesirable ways. We also changed the placeholder so that instead of multiple overlaid letters we now used a "%" symbol of the same size. Finally, we also removed the mirrored letters condition and showed all letters in their typical orientation.

Chapter 6: General Discussion

Summary

One of the essential underlying cognitive processes for human behavior is our ability to select information in the environment, while also ignoring other irrelevant, or even distracting, information. This ebb and flow of inhibition and selection is the hallmark of the human attentional system. When we introspect on the human capacity to attend to information, it rarely comes to mind that our ability to attend depends in large part on our ability to ignore. The interaction of inhibitory and excitatory processes of attention has been a much-debated topic in psychology, cognitive science, and neuroscience.

In my dissertation, I explored several avenues for probing the underlying structure of the *dark side of attention*, i.e., the underlying inhibitory processes that take place during the selection of information. First, in Chapter 2 I demonstrated that *learning* can play a critical role in whether to-be-ignored information is costly or beneficial. Across three experiments (Experiment 1, 2a, and 2b) I demonstrated that having a consistent to-be-ignored feature cue can result in a benefit, however this benefit is modulated by participants' time spent learning about the to-be ignored feature, where more learning results in more of

a RT benefit for ignoring the to-be-ignored feature. Next, in Chapter 3 I demonstrated, across two paradigms, that distractor feature information, rather than target feature information, seems to be critical in driving early feature-based attention. Building on previous work in this domain, I demonstrated with ERP and behavioral results that early feature-based attention can be facilitated by suppression of distractor feature information, on average, when multiple (i.e., two) distractor features are present. Importantly, we found that the context dependence of the mapping of the information (i.e., the feature mapping of what colors are the target and distractors should be consistent) seems critical to successfully suppress multiple distractor features. In Chapter 4, I demonstrated that lived and biologically driven experiences can influence our inability to inhibit certain stimuli. Using energy-dense food as an example, I showed how these totally irrelevant stimuli can grab our attention even in the face of a very demanding attentional task. Moreover, I demonstrated that local changes to goal-state(s) related to food (i.e., how recently you have eaten a small snack) can change whether or not you would be captured by these energy-dense food distractors. Finally, in Chapter 5, I explored the underlying structure of one of the most common ERP neural markers for attention and distraction (i.e., the N2pc). I showed that despite considerable previous work on characterizing the nature of this ERP component as a neural marker for the initial shift of attention

to a stimulus, it seems that this marker could also be referencing post-selection processing, much later than the initial shift.

How do my findings fit within current models of attention?

Due to the complicated nature of the variety of processes that are attributed to *attention* it has been difficult to come up with a unifying account or single computational model to illustrate the mechanisms of attention. However, many parts of attention have been described through several successful models (see review in Chapter 1). The goal of my work in this dissertation was to build on several aspects of the inhibitory mechanisms that support attention in hopes of better understanding how much they contribute to overall attentional processes in vision. Two modern models of attention that can account for these findings are: (1) Guided Search and (2) Biased competition.

Guided Search

Several of my reported results fit well within the *Guided Search* model of visual search (Wolfe, 1994b; Wolfe, 2001; Wolfe et al., 1989; Wolfe & Gancarz, 1997). Moreover, the results on the white bear effect in Chapter 2 pose an interesting situation for the Guided Search model. Typically, in Guided Search there is a massive parallel stage which accounts for the "bottom-up" saliency differences

in the display that would draw attention. Additionally, there is a top-down map that accounts for attention toward "target features." Interestingly, one explanation for our white bear effects is that observers first attend to the to-be-ignored information and then reject it. It seems that when given an explicit to-be-ignored cue, this becomes the "target" or initial goal output for the first instance of guidance in the Guided Search model. However, this leads to a couple of interesting questions. First, after the to-be-ignored item is rejected, how then is this information held in memory such that attention can move from the to-be-ignored information to the target that is present somewhere else in the display? Wolfe suggests that while they have shown no evidence of memory for "rejected distractors" in their work, other findings have lead them to include a weight in their model that allows for some "memory" of rejected distractors. However, this weight for rejected distractors is probabilistic such that it could be the case that the to-be-ignored item is resampled again if the search were complicated enough. Could it be the case that if there were a large enough visual set size, an explicit to-be-ignored item could be sampled again? Additionally, similar to other results in the literature (Arita et al., 2012; Becker, Hemsteger, & Peltier, 2016; Moher & Egeth, 2012), I suggest that observers deal with these "white bear effects" by developing a template for rejection. How does the Guided Search model account for negative attentional templates?

More specifically, where does the act of inhibition of the goal or guided information get implemented? It seems that in the most recent iteration of the Guided Search model (i.e., 4.0) these results can be explained by the feedback stage from the "Decision" (Wolfe, 2001). Specifically, as with other selected distractors (i.e., not explicitly cued ones), the to-be-ignored item will be rejected and a subsequent search will take place through the remaining items. It seems that the difference between a to-be-ignored distractor and any other distractor is that attention is guided more strongly to the to-be-ignored distractor by the explicit to-be-ignored cue. Overall, it seems that Guided Search can, for the most part, account for our learned distractor rejection results from Chapter 2.

In addition to the results from Chapter 2 on the white bear effect, my ERP and behavioral results from Chapter 3 on early feature-based attention also present some interesting findings that support claims in the "activation maps" portion of the Guided Search model (Wolfe, 1994a). In Chapter 3, we found a very early top-down signal that suppresses distractor color features resulting in a difference in the P100 ERP component. In Guided Search (Wolfe, 1996), the feature maps that feed into the combined "activation map", which subsequently is where the guidance signal is drawn from, can fully account for my results. Specifically, in my TSD paradigm there is a top-down signal to attend to one

color (e.g., red) and ignore two other distractor colors (e.g., blue and green). This would result in an activation map where the two distractor colors would be down-weighted (e.g., resulting in two negative or lower peaks) and the target information could either remain neutral (which seems to be the case from our ERP results) or it could also benefit from excitation (e.g., higher peaks). Then when guidance is drawn from this activation map, the relative difference between the distractor colors and target colors would result in an increased signal to the target color feature. Moreover, it seems that my results suggest that the P100 might be tapping into some form of the relationships in this activation map, at least for color features in the TSD paradigm. Furthermore, this is also supported by the fact that the P100 is at a much earlier time point than typical attentional components (e.g., N2pc/Pd). One interesting point to consider is that in my follow-up experiment, i.e., the multiple varying distractor (MVD) paradigm, it seems that the directionality of the P100 difference is positive compared to the results from the TSD paradigm and previous work by Moher et al. (2014). While this presents makes the data a bit more difficult to interpret, it seems that the P100 could still be tapping into this activation map, rather the directionality of the differences aren't as important as the differences among the categories of features that are present (i.e., neutral, target, and distractor colors).

Biased Competition

Some of the results reported here could also pose interesting questions for another model of attention: Biased Competition (Desimone & Duncan, 1995). In Biased Competition, similar to Guided Search, there is competition between Bottom-up and Top-down signals. The "winner" in these situation is then what is selected/attended. As mentioned previously, the classic top-down/bottom-up dichotomy could easily account for our results related to attentional capture by energy dense foods. It seems that Biased Competition is a parsimonious computational approach to how this might be implemented. For example, it seems that while there might be any number of underlying top-down signals at play in a task like this: hunger signals, food signals for driving attention to particularly tasty foods, goal signals to finish the task quickly. All of these would be in direct competition with one another. The "winner" in these experiments seems to be more often than not the abrupt onset of an energy-dense food, when other hunger goals are not in the competition. However, once a participant has recently consumed a small snack, this appears to down-weight any competition from the energy-dense food and competition is resolved in favor of the main task. One interesting question to consider is how are all of these "goals" represented such that they could be compared to one another?

What common bias space must exist to be able to compute the weight of hunger verses the power of an abrupt onset? While the questions cannot be answered with the current results presented here, the Biased Competition model does create a simple yet effective framework for thinking about the complicated structure of all the sources of competition in our distraction work on energy-dense foods.

Concluding remarks

Overall, my work on the inhibitory mechanisms of attention has further illustrated the critical role that ignoring plays in attentional processes. Much of this work adds to the current conversations and frameworks within the attention literature by highlighting the importance, and necessity, in understanding the inhibitory mechanisms of attention. Across several paradigms I have shown how ignoring not only can play a critical role in attentional processing but in many cases, processes related to inhibition are often handled prior to any processes related to target excitation. Thus, one could argue that in some circumstances that inhibition drives the initial wave of attention. Continuing to explore and delve into the inhibitory processes of attention seems crucial for developing a unifying framework/model for understanding visual attention in humans.

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PERSONAL DATA

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DEGREES AND EDUCATION

2012-present	The Johns Hopkins University, Baltimore, Maryland Department of Psychological and Brain Sciences **PhD Candidate** Advisor: Dr. Howard Egeth
2014	The Johns Hopkins University, Baltimore, Maryland Department of Psychological and Brain Sciences **Master of Arts in Psychological and Brain Sciences** Advisor: Dr. Howard Egeth
2010	The University of Washington, Seattle, Washington **Bachelor of Science in Psychology**

RESEARCH EXPERIENCE

Sep 2012-present	**Graduate Research Fellow, The Johns Hopkins University Department of Psychological and Brain Sciences, Baltimore, MD** Attention and Perception Lab Advisor: Dr. Howard Egeth Research includes top-down influences on attention, feature-based inhibition, visual search, neural mechanisms of attention (EEG/ERP techniques), and visual long-term memory.
Aug 2010-July 2012	**Research Assistant, Harvard Medical School and Brigham & Women's Hospital, Cambridge, MA** Visual Attention Lab Advisors: Dr. Jeremy Wolfe and Dr. Todd Horowitz Conducted psychophysical research on the nature of visual attention (visual attention, visual search in medical images, and

object recognition). Collected and analyzed eye movement data for various eye-tracking studies. Collected EEG data. Organized and updated IRB protocols.

Sep 2008-Aug 2010 **Undergraduate Research Assistant, University of Washington Department of Psychology, Seattle, WA**
Human Color Vision Lab
Advisor: Dr. Steven Buck
Conducted psychophysical research related to rod influence on cones. Studied intrinsically photosensitive retinal ganglion cells. Configured and ran Maxwellian-view apparatus.

PUBLICATIONS

Cunningham CA & Egeth HE. (*forthcoming)* "The capture of attention by entirely irrelevant pictures of calorie-dense foods." *Psychonomic Bulletin & Review.*

Hout MC, **Cunningham CA**, Robbins A, & MacDonald J. (*forthcoming*) "Simulating the fidelity of data for large stimulus set sizes and variable dimension estimation in multidimensional scaling." *SAGE Open.*

Draschkow D, Reinecke S, **Cunningham CA** & Võ ML. "The Lower Bounds of Massive Memory: Investigating memory for object details after incidental encoding" (*forthcoming*). *Quarterly Journal of Experimental Psychology.*

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OTHER ARTICLES (NON-PEER REVIEWED PUBLICATIONS)

Spiker ML & **Cunningham CA** (2015) "Food Access and Waste Reduction: Proposal for a Vendors' Market in Baltimore City." *Abell Award in Urban Policy.*

Gonzales JE & **Cunningham CA** (2015) "The Promise of Pre-registration in Psychological Research" *American Psychological Association: Psychological Science Agenda.*

Cunningham CA & Gonzales JE (2014) "The Golden Age of Data Sharing: How to Prepare Data for Open Access" *American Psychological Association: Psychological Science Agenda.*

PEER-REVIEWED CONFERENCE TALKS

Schurgin MW, **Cunningham CA**, Egeth HE, & Brady TF. "Episodic Memory Replaces Active Maintenance in Working Memory When Available." *Vision Sciences Society 18th Annual Meeting*, St. Petersburg, FL. May, 2018.

Schurgin MW, **Cunningham CA**, Egeth HE, & Brady TF. "The effect of episodic memory on active storage in visual working memory." *Object Perception, Attention, and Memory (OPAM*), Vancouver, BC. November 2017.

Cunningham CA & Egeth HE. "Real World Goals Are Fickle and Volatile: Consuming High Fat Foods Reduces Distraction from Entirely Irrelevant High-Fat Foods." *Vision Sciences Society 15th Annual Meeting*, St. Petersburg, FL. May, 2016.

Cunningham CA & Kuo PX "Beyond Federal Funding---Seeking Out Funding Opportunities From Private Institutions and Foundations" *American Psychological Association Annual Meeting*, Toronto, Ontario August, 2015 (Session Chair).

Wolfe JM, Drew T, Boettcher S, Josephs E, & **Cunningham CA** "The (Minimal) Role of Familiarity in Hybrid Visual and Memory Search." *Psychonomic Society Annual Meeting*, Long Beach, California. November 2014.

Cunningham CA & Gaffey A. "Navigating the National Funding Climate: Why What Happens on Capitol Hill Matters" *American Psychological Association Annual Meeting*, Washington, D.C. August, 2014 (Session Chair).

Wolfe JM, Drew T, Boettcher S, & **Cunningham CA**. "Hybrid Search: How do visual search and memory search work together?" *Talk presented at the Vienna Science and Technology Fund Meeting*, Vienna, AU. June, 2013.

Cunningham CA & Wolfe JM. "Lions or tigers or bears: Oh my! Hybrid visual search for categorical targets." *Object Perception, Attention, and Memory (OPAM)*, Minneapolis, Minnesota. November 2012.

Buck SL, **Cunningham CA**, DeWenter RJ, Levens R, Nguyen A, & Wurden C. "Rod influence on appearance of desaturated hues." *Bienniel Symposium of the International Colour Vision Society*, Braga, Portugal. July, 2009.

PEER-REVIEWED CONFERENCE POSTERS

Chang S, **Cunningham CA**, & Egeth HE. "The Power of Negative Thinking: Paradoxical but Effective Ignoring of Salient-but-Irrelevant Stimuli by a Spatial Cue." *Vision Sciences Society 18th Annual Meeting*, St. Petersburg, FL. May, 2018.

Chang S, **Cunningham CA**, & Egeth HE. "Active Inhibition of Attentional Capture by Irrelevant-but-Salient Stimuli." *Object Perception, Attention, and Memory (OPAM)*, Vancouver, BC. November 2017.

Cunningham CA, Moher J, Tran A, Hoffman JE, & Egeth HE. "The Neural Mechanisms of Learning to Ignore." *Vision Sciences Society 17th Annual Meeting*, St. Petersburg, FL. May, 2017.

Cunningham CA, Blackstock PE, & Egeth HE. "Revealing the existence of distractor suppression during stimulus-driven attentional capture." *Object Perception, Attention, and Memory (OPAM)*, Boston, Massachusetts. November 2016.

Robbins A, **Cunningham CA**, MacDonald J, & Hout MC. "Strength in numbers: Testing the fidelity of multidimensional scaling for large datasets." *Psychonomic Society Annual Meeting*, Boston, Massachusetts. November, 2016.

-Also presented at the ARMADILLO Cognition Conference: El Paso, TX (September, 2016).

Madrid J, Godwin H, **Cunningham CA**, Robbins A, & Hout MC. "All targets are not created equal: Some targets are often missed in hybrid visual search tasks." *Object Perception, Attention, and Memory (OPAM)*, Boston, Massachusetts. November 2016.

-Also presented at the ARMADILLO Cognition Conference: El Paso, TX (September, 2016).

Madrid J, **Cunningham CA**, Robbins A, Godwin H, Wolfe JM, & Hout MC. "Exploring the nature of mental representations in hybrid visual and memory search." *Vision Sciences Society 15th Annual Meeting*, St. Petersburg, FL. May, 2016.

Cunningham CA, Ewen JB, & Egeth HE. "Inhibition Drives Early Feature-based Attention (even when there are multiple distractor features)." *Object Perception, Attention, and Memory (OPAM)*, Chicago, Illinois. November 2015.

Madrid J, **Cunningham CA**, Robbins A, & Hout MC "Don't label me!: Search for familiar, nameable objects vs. search for unfamiliar, novel objects." *Object Perception, Attention, and Memory (OPAM*), Chicago, Illinois. November 2015.

Cunningham CA & Egeth HE. "Loosening the Snare: Top-down goals overcome singleton driven attentional capture." *Vision Sciences Society 15th Annual Meeting*, St. Petersburg, FL. May, 2015.

Cunningham CA & Egeth HE. "When Constant Rejection is a Good Thing: the effects of learning on efficient feature inhibition." *Object Perception, Attention, and Memory (OPAM*), Long Beach, California. November 2014.

Cunningham CA, Pailian H, & Egeth HE. "Characterizing Representations in Activated Long-Term Memory." *Psychonomic Society Annual Meeting*, Long Beach, California. November 2014.

Loiotile RE**, Cunningham CA,** Egeth HE, & Courtney SM. "Behavioral pattern separation/completion: A signal detection theory analysis" *Society for Neuroscience Annual Meeting*, Washington D.C., November 2014.

Cunningham CA & Egeth HE. "Learning to Ignore Non-target Features Eventually Leads to More Efficient Search." *American Psychological Association Annual Meeting*, Washington, D.C. August, 2014.

Cunningham CA & Egeth HE. "Taming the White Bear: Learning Distractor Features Begins With a Cost, But Eventually Allows For More Efficient Search." *Vision Sciences Society 14th Annual Meeting*, St. Petersburg, FL. May, 2014.

Cunningham CA, Yassa MA, & Egeth HE. "Massive memory revisited: estimating object details in visual long-term memory." *Object Perception, Attention, and Memory (OPAM*), Toronto, Ontario. November 2013.

Cunningham CA, Wolfe JM, & Egeth HE. "Incidental memory for potential targets vs. confirmed distractors" *Vision Sciences Society 13th Annual Meeting*, Naples, FL. May, 2013.

Cunningham CA & Wolfe JM. "Extending "Hybrid" Visual X Memory Search to Very Large Memory Sets and to Category Search." *Psychonomic Society Annual Meeting*, Minneapolis, Minnesota. November 2012.

Cunningham CA & Wolfe JM. "Finding what is new in hybrid visual and memory search: a new search asymmetry." *Vision Sciences Society 12th Annual Meeting*, Naples, FL. May, 2012.

Drew T, **Cunningham CA**, & Wolfe JM. "Why does Computer Aided Detection interfere with visual search?." *Medical Image Perception Conference (MIPS),* Dublin, Ireland. August 2011.

Cunningham CA & Sherman A. "Beyond Where's Waldo: Visual Search in the Real World." *Harvard Medical School: Project Success 2011,* Boston, Massachusetts. August 2011.

Drew T, **Cunningham CA**, & Wolfe JM. "Helping Computer Aided Detection (CAD) help you: Increasing the behavioral benefit of a given CAD signal." *European Conference on Visual Perception,* Toulouse, France. August 2011.

Cunningham CA, Drew T, & Wolfe JM. "When and why does Computer Aided Detection (CAD) interfere with visual search?" *Vision Sciences Society 11th Annual Meeting*, Naples, FL. May, 2011.

Drew T, **Cunningham CA**, & Wolfe JM. "Why don't Computer Aided Detection (CAD) algorithms help experts as much as they should?" *Vision Sciences Society 11th Annual Meeting*, Naples, FL. May, 2011.

Buck SL, & **Cunningham CA**. "Rod influence on appearance of desaturated hues." *The Optical Society of America Vision Meeting 2009*, Seattle, WA. September 2009.

MEDIA ATTENTION (SELECTED PRESS COVERAGE FROM 100+ MEDIA SOURCES)

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Hicks, J. (2016, February 26). Scientists Say Your Ability To Ignore Is Part Of Your Ability To Pay Attention. *Forbes*. Retrieved from http://www.forbes.com/sites/jenniferhicks/2016/02/26/scientists-say-your-ability-to-ignore-is-part-of-your-ability-to-pay-attention/#789b921b2a87

Mikulak, A. (2016, February 25). Mastering the Art of Ignoring Makes People More Efficient. *Association for Psychological Science*. Retrieved from http://www.psychologicalscience.org/index.php/news/releases/mastering-the-art-of-ignoring-makes-people-more-efficient.html

HONORS AND AWARDS

HONORS

2016	Best Poster Award, 24th Annual Object Perception, Attention, and Memory (OPAM) Conference
2015	Abell Award in Urban Policy
2015	Johns Hopkins University Department of Psychological and Brain Sciences, Walter L. Clark Service Award
2014	Best Student Poster, APA Convention 2014: Division of Experimental Psychology
2010	University of Washington Dean's List
2008	Central Washington University Dean's List

ACADEMIC FUNDING

2016	National Science Foundation Graduate Research Opportunities Worldwide Fellowship
2016-2018	Distinguished Science of Learning Fellowship Science of Learning Institute, Johns Hopkins University
2013-2016	National Science Foundation Graduate Research Fellowship
2015	Johns Hopkins University Department of Psychological and Brain Sciences Off-Campus Research Expansion Award (OREA)
2008, 2009	University of Washington Academic Competitiveness Grant

CONFERENCE TRAVEL FUNDING

2015	The Johns Hopkins University Graduate Representative Organization (GRO) Travel Award
2014	Travel Award for the American Psychological Association Convention in Washington, D.C.
2012	Travel Award for the Object Perception, Attention, and Memory (OPAM) Conference in Minneapolis, MN

TEACHING EXPERIENCE

Winter 2017	Instructor of Record, Food for Thought, Johns Hopkins University
Fall 2016	Lead Instructor, Research Methods in Exp. Psychology, Johns Hopkins University
Fall 2015	Lead Instructor, Research Methods in Exp. Psychology, Johns Hopkins University
Fall 2014	Instructor, Research Methods in Exp. Psychology, Johns Hopkins University
Spring 2014	Teaching Assistant, Introduction to Cognitive Psychology, Johns Hopkins University
Fall 2013	Teaching Assistant, Introduction to Psychology, Johns Hopkins University
Spring 2013	Teaching Assistant, Altered States of Consciousness, Johns Hopkins University

LEADERSHIP AND GOVERNANCE

2017	Director of Psychological & Brain Sciences High School Engagement Program
Spring 2014, 2015	Board of Scientific Affairs Liaison for APA Spring Consolidated Meeting
2013-2015	Chair (Cognitive Science Representative) of the American Psychological Association Science Student Council
2013-2015	Organizer & Leader for Psychological and Brain Sciences Graduate Student Recruitment

PROFESSIONAL AFFILIATIONS

2014-present	Association for Psychological Science
2013-present	American Psychological Association
2011-present	Vision Science Society
2010-2012	The Center for Advanced Medical Imaging (BWH/Harvard Medical School)
2009	Optical Society of America